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PRINCIPLES OF THE DRYING PROCESS WITH SPECIAL REFERENCE TO VEGETABLE DEHYDRATION

(A revision of the section entitled "Principles Involved in the Drying Process", in U.S.D.A. Miscellaneous Publication No. 540, "Vegetable and Fruit Dehydration, a Manual for Plant Operators", June, 1944.)

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PRINCIPLES OF THE DRYING PROCESS,

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FOREWORD

Beginning shortly before World War II the U. S. Department of Agriculture inaugurated a comprehensive program of research on food dehydration, aimed to achieve quickly a body of scientific and technological information upon which a great industry could be built rapidly and soundly. In June, 1944, the Department issued its Miscellaneous Publication No. 540, "Vegetable and Fruit Dehydration--A Manual for Plant Operators". This was a booklet of 218 pages, bringing together the early results of the Department's research program and the best possible statement of existing knowledge about large-scale food dehydration. It has been out of print for several years.

During the time since M.P. 540 was written significant new research advances have been made, and the industrial technology of food dehydration has advanced far beyond its state in 1943. It is anticipated that eventually a completely revised edition of the bulletin will be published.

The present Bureau Circular is a revision of one main section of M.P. 540, which was entitled "Principles Involved in the Drying Process". Its main emphasis is on vegetable dehydration.

Most of the technical books and periodicals referred to in this bulletin are available in the larger public libraries and the libraries of State universities. The reader who wishes to consult the original articles, but who cannot conveniently visit such a library, should inquire about the procedure for obtaining photostatic copies by writing to the librarian at his State university, the librarian of the U. S. Department of Agriculture, Washington, D. C., or the librarian of the Western Regional Research Laboratory, Albany, California.

INTRODUCTION

The characteristic operation in food dehydration is drying, that is, the removal of water by vaporization. Since the product will be acceptable for food uses only if it resumes a good color, flavor, texture, and nutritive value when water is added back to it, the conditions of drying must be carefully chosen to do as little injury to these qualities as possible. Within the limits thus imposed, however, there remains an opportunity for the dehydrator operator to increase the output of his equipment, fit it smoothly into the chain of operations that precede and follow drying, and make economies in operating cost. The operator will need experience to recognize such opportunities and to diagnose and remedy the troubles which may develop; but personal experience can be powerfully reinforced by intelligent understanding of the experience of hundreds of other people, summarized in the form of accepted general principles.

The following sections of this bulletin explain these principles, beginning with a description of the way water vapor behaves in air, going on to a discussion of the removal of water from a moist solid, and ending with consideration of the way warm air and moist solid interact on one another in a dehydrator. Insofar as possible the explanations have been made quantitative; that is, useful calculations are emphasized. Of course no amount of pencil-and-paper work will substitute for practical trial of a new idea, but often a little advance calculation will save useless effort and open ones eyes to the real possibilities. Numerous examples are worked out in the text. One which appears in the last section of this bulletin is typical of the kind of thing which can be calculated with little effort: Potato half-dice are being dried in a counterflow tunnel, with a hot-end temperature of 160° and a wet-bulb temperature of 110°; how much increase in output of dry product will there be if the recirculation damper is closed completely, and how much additional heat will then be required to operate the dehydrator?

I. THE PROPERTIES OF AIR AND WATER VAPOR

This chapter presents a description of the manner in which water evaporates, defines the terms used in the study of drying, and describes methods used in measuring air velocity and humidity. These matters are discussed specifically with reference to vegetable dehydration. More comprehensive treatment will be found in the standard textbooks and handbooks of chemical engineering.

I-A. The Vaporization of Water

The evaporation of water from a wet article is so commonplace an occurrence that everyone takes it quite for granted. An explanation of the things that take place during drying must go deeply, however, into the consequences of physical laws. The mechanism is most easily pictured in terms of the molecular theory.

The molecule is defined as the smallest particle of matter which possesses the same physical properties as a large quantity of the same substance. Further subdivision of this particle into the atoms of which it is composed would result in a mixture of completely different substances. The molecule of water is an extremely small particle. A single drop of water contains about 1000 billion billion of them. Some of the complex molecules of which living tissues are composed are thousands of times heavier than a water molecule; some of them are threadlike, others are branched, or coiled, or condensed into a tight ball.

The molecules in a body of liquid water are in incessant jostling motion, much like the people on a crowded dance floor. The temperature of the water is a measure of the vigor of this molecular motion. A rise in temperature means an increase in the average speed of molecular movement. Just as on the dance floor, more space is required for the assemblage if the molecules are moving rapidly than if they are moving slowly; the liquid expands as the temperature rises. The accidents of head-on and glancing collisions give rise to a wide variation in the speeds of different molecules. A very few will be momentarily moving very fast, a very few will be momentarily stationary.

At the surface of the body of liquid water a molecule which happens to be moving upward very fast will break away completely from the attraction of the surrounding crowd and will "evaporate" into the air above the water. There it finds itself caught up in a very different kind of dance. Molecules of oxygen and nitrogen, each about twice as heavy as the water molecule but much less strongly attracted to one another than the molecules in liquid water, are moving so fast that almost 1000 times as much space is required to accommodate the same number of them. The water molecule becomes a part of this fast-moving crowd. Other water molecules follow it from the water surface into the air space.

Eventually some of these molecules of water vapor, acquiring an especially rapid downward push toward the liquid surface, will reenter the liquid and be caught by its attraction again. If the air space above the water is enclosed, this two-way traffic will go on indefinitely, but finally the number of water molecules leaving the liquid in any interval of time will just equal the number returning to the liquid from the air space. When that is the case, the air space is said to be "saturated" with water vapor.

Physicists and engineers have made very careful measurements to define this condition of saturation. The following general characteristics of what they find are important to the present discussion:

1. The higher the temperature, the greater the amount of water vapor present in the saturated vapor space.

2. The amount of water vapor in the saturated vapor space is very nearly the same, whether or not air is also present in this space.

It should be apparent, from the very definition of a "saturated" vapor, that drying can **take** place only into a space that is less than saturated with vapor, because only then can there be a greater rate of loss of moisture than of regain of moisture from the vapor.

I-B. Vapor Pressure

The water vapor in an enclosed space exerts, like any gas or vapor, a pressure on all the walls of the container which is the sum of all the minute impulses produced by collision of its molecules with the walls of the vessel. At a given temperature this pressure is proportional to the number of molecules in unit vapor space, and at a given concentration of molecules it is proportional to the temperature of the vapor, measured from the physicists' "absolute zero", 459.6 degrees below zero Fahrenheit.

Measurements of the pressure of water vapor in a saturated vapor space are summarized in Table 1[1]. The pressure, expressed in terms of the height of a mercury column, in inches, which will just balance it, is defined as the "vapor pressure" of water at the given temperatures.

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[1] Goff, J. A. and Gratch, S. Thermodynamic Properties of Moist Air. Htg., Piping, and Air Condg., Jour. Sec., 17(6):334-48, June, 1945.

Table 1

Vapor Pressure of Water

Temperature °F.	Vapor Pressure of Water Inches of Mercury	Temperature °F.	Vapor Pressure of Water Inches of Mercury
0	0.0376	160	9.656
10	.0629	170	12.20
20	.103	180	15.29
30	.165	190	19.02
40	.248	200	23.47
50	.362	210	28.75
60	.522	212	29.92
70	.739	220	35.0
80	1.032	230	42.3
90	1.422	240	50.8
100	1.933	250	60.7
110	2.597	260	72.1
120	3.447	270	85.1
130	4.527	280	100.1
140	5.884	290	117.2
150	7.572	300	136.4

The vapor pressure of water at 212° F. is given in Table 1 as 29.92 inches of mercury. But this is the mean pressure of our atmosphere at sea level. When the vapor pressure of the liquid equals the pressure in the gas space above it, vapor bubbles can form in the liquid itself. This is what happens when the liquid boils. The boiling point of water at sea-level atmospheric pressure is 212° F.

I-C. Partial Pressure and Relative Humidity

An experimental observation referred to above is that the amount of water vapor in a saturated vapor space is very nearly the same, whether or not air is also present in the same space. A related fact is that the "total pressure" of a mixture of air and water vapor is the sum of the pressures exerted by the separate components. Thus in a vessel containing water, but open to the atmosphere so that the total pressure in it is atmospheric, the "partial pressure" of the air will be less than atmospheric; the water vapor will have crowded out part of the air.

If a sample of air is completely free from water vapor the partial pressure of water vapor in it is, of course, zero. At the other extreme[2] the partial pressure of water vapor in a space saturated with water vapor

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[2] (Except for the phenomenon of supersaturation, with which we are not concerned here, although it is important in meteorology.)

at some temperature is equal to the vapor pressure of water at that temperature. Below the latter extreme the air is only partially saturated, can take up more water vapor, and therefore can cause the drying of a wet object.

A common measure of the degree of saturation of the air is the relative humidity (R.H.), which is simply the ratio of the partial pressure of water vapor in the air to the vapor pressure of water at the same temperature, expressed as a percentage. That is,

$$\text{R.H.} = 100 \frac{p}{P_s} \quad - - - - - - - - \quad (1)$$

In this formula the symbol p signifies the partial pressure of water vapor in the air, P_s the vapor pressure of water. The units in which p and P_s are expressed are immaterial--that is, they may be expressed in millimeters of mercury, inches of mercury, pounds per square inch, or atmospheres--so long as they are both in terms of the same unit.

A relative humidity of zero signifies that the air contains no water vapor, a relative humidity of 100 percent means that the air is saturated with water vapor at that particular temperature. The average relative humidity of outdoor air in the United States, winter and summer, is about 65 percent. On hot afternoons in arid regions it may fall to only 10 or 15 percent. Air that is on the verge of becoming foggy has a relative humidity of nearly 100 percent.

If air is heated or cooled at constant total pressure and without any change in the quantity of water it contains, its relative humidity changes. The partial pressure of water vapor in the air will remain constant, but the vapor pressure of water will rise if the temperature rises, fall if the temperature falls (see Table 1). The change in relative humidity will be substantial even for small changes in temperature, as is illustrated in Figure 1. The two curves in that diagram show what happens to the relative humidity of air whose R.H. is either 65 percent at 0° F. or 65 percent at 80° F., if the temperature changes. The zero-degree air becomes even less humid than desert air if it is warmed to 70°, although its actual moisture content remains unchanged. People who live in regions of severe winter cold experience this desert dryness inside their heated homes unless they artificially humidify the air. The other curve of Figure 1 shows that air whose relative humidity is 65 percent at 80° F. becomes saturated if it is cooled to only a few degrees below 70° F. On the other hand, if it is heated to 150° F., a common dehydrator temperature, its relative humidity falls to only about 10 percent, again a condition of desert dryness.

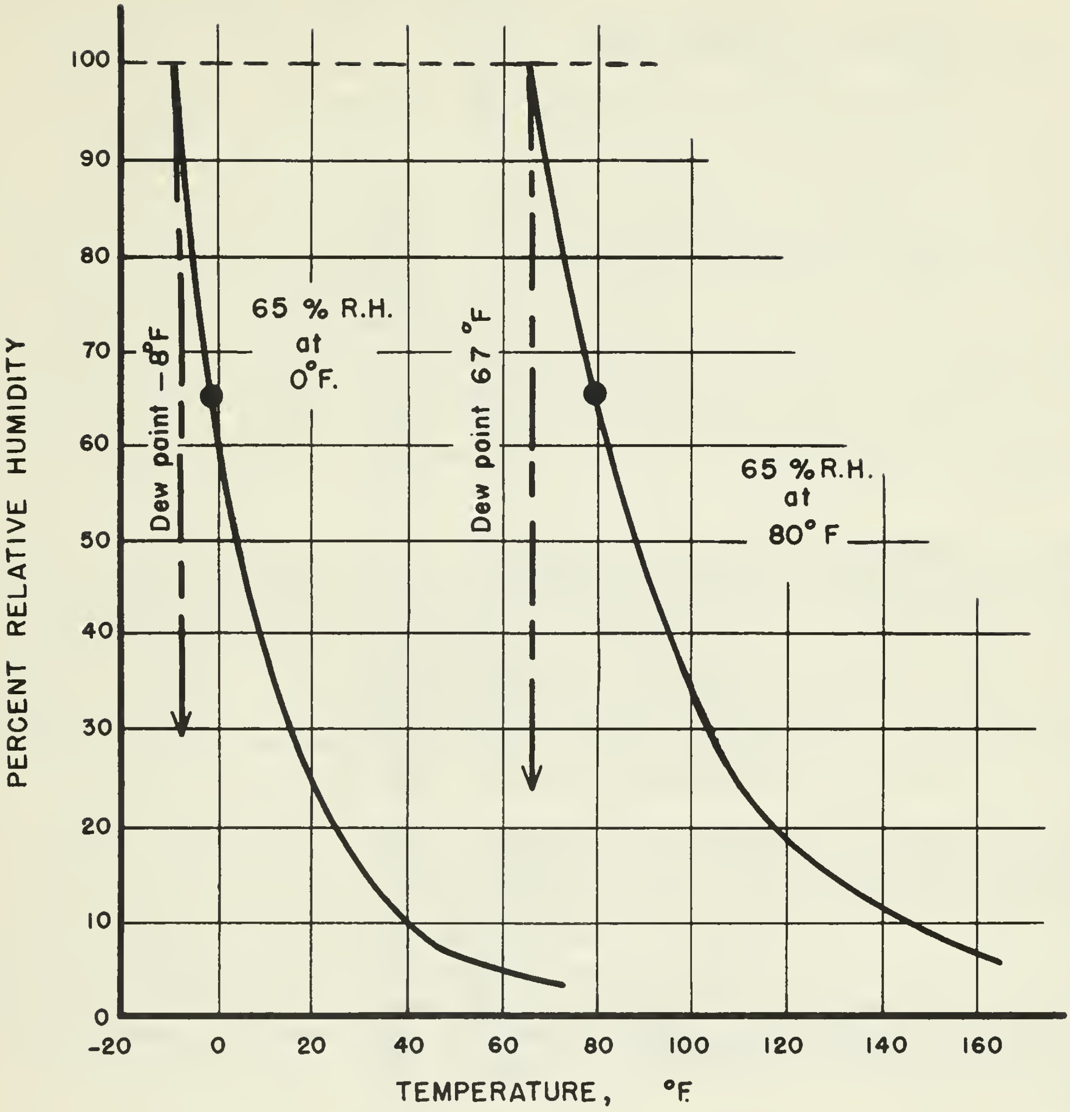

FIGURE I — CHANGE IN RELATIVE HUMIDITY AS AIR IS WARMED OR COOLED

I-D. Other Measures of Humidity

Two other physical quantities, namely the dew-point temperature and the absolute humidity, also may be used to specify the proportion of water vapor in air. In some dehydrator calculations they are more useful measures of the moistness of air than the relative humidity.

The dew-point temperature of a mixture of water vapor and air, usually known simply as the dew point, is that temperature at which the mixture would become saturated with water vapor if it were cooled without change in total pressure or composition. Thus if the mixture is already saturated its dew point coincides with its temperature, while if it is less than saturated its dew point is lower than its temperature. Referring to Figure 1, the dew point of air which has a relative humidity of 65 percent at 80° F. is about 67° F. The same dew point will evidently characterize any point on that same relative humidity-temperature curve--for example, air whose relative humidity is 15 percent at 130° F. also has a dew point of 67° F. In fact, this dew point corresponds with a certain partial pressure of water vapor--in this case 0.667 inches of mercury--regardless of the temperature or pressure of the mixture. Note, then, that if an air-water vapor mixture is either heated or cooled without change in total pressure its dew point remains unchanged. And with respect to dehydrator practice, the lower the dew point of the air supply, the drier that air is and the greater is its capacity for taking up additional moisture.

The absolute humidity of an air-water vapor mixture is defined as follows: Absolute humidity = pounds (or grains) of water vapor per pound of dry air (1 pound equals 7000 grains). In air conditioning calculations the absolute humidity is often expressed in grains of water vapor, but in this bulletin it will always be expressed in pounds. Under all ordinary conditions it is a small fraction. The average summer and fall absolute humidity in most sections of the United States ranges from about 0.005 to 0.015 pound of water vapor per pound of dry air (see Table 2).

Like the dew point, the absolute humidity remains unchanged if the air is heated or cooled, but in addition the absolute humidity also remains constant if the pressure of the air is increased or decreased. It is a particularly useful measure of humidity in dehydrator calculations because it is expressed on a weight basis. A pound of dry air entering a dehydrator, for example, still weighs just a pound at any other point during its passage through the system, no matter what changes in temperature or pressure may have taken place, or how much water vapor may have been added to it.

Studies of the relation of human comfort to atmospheric conditions have shown that relative humidity correlates closely with comfort or discomfort. This "feel" of the air is no guide to its usefulness as air supply for a dehydrator. Air that feels very moist on a chilly day, with a temperature of, say, 40°, is likely to contain less moisture than air that feels "dry" and comfortable at 80°. It is almost always a mistake to draw the air supply for a dehydrator from inside the plant building, for that air will usually have a higher absolute humidity than the outside air, even though, being warmer, it may feel much drier. If a location for a dehydration plant is being chosen, Weather Bureau records of dew point are much more pertinent than the records of relative humidity.

Table 2

Mean Barometric Pressure, Dew Point, and Absolute Humidity at Selected Cities in the United States

Place	Elevation Feet	Mean Barometric Pressure Inches	January			April			July			October		
			Mean Monthly			Mean Monthly			Mean Monthly			Mean Monthly		
			Temperature °F.	Dew Point °F.	Absolute Humidity Lb./Lb.	Temperature °F.	Dew Point °F.	Absolute Humidity Lb./Lb.	Temperature °F.	Dew Point °F.	Absolute Humidity Lb./Lb.	Temperature °F.	Dew Point °F.	Absolute Humidity Lb./Lb.
Portland, Maine	103	29.87	20.5	13	0.0015	42.5	33	0.0039	68.4	61	0.0115	49.5	42	0.0056
Buffalo, New York	768	29.18	24.1	19	.0021	44.5	35	.0044	71.0	61	.0117	52.7	45	.0065
Philadelphia, Penna.	114	29.92	32.6	23	.0025	52.1	38	.0048	76.2	65	.0132	57.8	47	.0068
Nashville, Tennessee	546	29.49	39.2	32	.0038	59.4	46	.0067	79.4	67	.0144	61.1	49	.0075
Charleston, S.C.	48	30.03	50.5	42	.0056	64.9	54	.0089	81.6	73	.0174	67.8	58	.0102
Miami, Florida	25	30.01	67.9	58	.0102	73.9	65	.0132	81.8	73	.0175	78.0	69	.0152
New Orleans, La.	?	30.04	53.2	43	.0060	67.8	59	.0106	82.4	73	.0174	70.0	61	.0114
St. Louis, Mo.	568	29.43	31.2	23	.0025	56.5	43	.0059	80.2	65	.0134	59.4	47	.0069
Minneapolis, Minn.	838	28.99	13.9	9	.0013	46.1	33	.0041	73.2	60	.0114	49.9	40	.0054
Bismarck, N. Dakota	1,660	28.22	8.5	6	.0011	43.3	29	.0035	70.6	56	.0101	45.4	33	.0042
Omaha, Nebraska	1,105	28.83	20.9	15	.0017	51.0	37	.0048	75.2	63	.0128	53.4	42	.0058
Denver, Colorado	5,283	24.70	30.6	19	.0025	47.8	33	.0048	72.6	52	.0100	51.6	35	.0052
Dallas, Texas	488	29.47	45.4	34	.0041	65.3	53	.0087	84.3	68	.0149	67.9	54	.0090
San Antonio, Texas	794	29.17	52.4	43	.0060	69.2	58	.0105	83.7	72	.0174	71.0	60	.0113
Phoenix, Arizona	1,106	28.74	50.0	33	.0041	69.0	36	.0046	91.0	56	.0100	71.0	45	.0066
Salt Lake City, Utah	4,227	25.73	25.4	22	.0028	50.2	33	.0046	76.8	36	.0052	52.7	26	.0033
Boise, Idaho	2,858	26.96	27.9	25	.0030	49.1	34	.0045	72.5	45	.0070	50.1	34	.0046
Spokane, Wash.	1,900	28.02	9.0	3	.0010	43.9	27	.0032	69.1	45	.0068	44.2	31	.0038
Seattle, Wash.	125	29.92	40.8	35	.0043	51.1	40	.0052	65.5	52	.0082	53.7	47	.0068
Portland, Oregon	154	29.91	39.4	34	.0041	55.8	46	.0066	66.7	54	.0089	54.2	43	.0059
Sacramento, Calif.	25	29.96	44.6	38	.0048	58.5	46	.0066	74.6	52	.0082	64.8	48	.0071
Oakland, Calif.	18	30.01	47.6	40	.0052	56.0	46	.0066	63.0	54	.0088	60.3	50	.0076
Fresno, Calif.	277	29.63	45.5	42	.0056	60.2	44	.0061	81.3	50	.0077	62.3	47	.0069
Los Angeles, Calif.	512	29.35	55.6	43	.0059	60.2	49	.0075	70.6	59	.0108	65.8	53	.0087

Relative humidity and absolute humidity values may be interconverted if the temperature and the barometric pressure are known. The following conversion equations are only approximate, but their accuracy is sufficient for practical purposes.

$$a = \frac{0.623\ p}{B - p}\ ,^{3/} \quad \text{- - - - - - - - - -} \quad (2)$$

$$a = \frac{0.623\ P_s\ (R.H.)}{100B - P_s\ (R.H.)}\ , \quad \text{- - - - - - -} \quad (3)$$

$$(R.H.) = \frac{100B}{P_s}\left(\frac{a}{a + 0.623}\right) . \quad \text{- - - - - - - -} \quad (4)$$

In those formulas the symbols have the following meanings:

a = absolute humidity, pounds water vapor per pound dry air
B = barometric pressure, inches of mercury; under mean sea-level conditions, $B = 29.92$.
p = partial pressure of water vapor, inches of mercury
P_s = vapor pressure of water at the given temperature, inches of mercury (Table 1)
R.H. = relative humidity, percent.

I-E. Methods of Measuring Humidity

Numerous ways of measuring the amount of water vapor in air are known, but several of them are useful only in a laboratory, and only three need be described here.

The hair hygrometer contains a fine strand of lightly stretched human hair, one end of the strand being fixed and the other being attached through a multiplying gear to a light, spring-opposed indicator hand. Holes allow air to circulate freely through the case. At low relative humidities the hair contracts and at high relative humidities it relaxes, or stretches. The indicator dial is usually calibrated to read relative humidity directly. Instruments of this kind are quite common for household use, and the same principle has even been applied in automatic humidity control instruments. The hair hygrometer does not, however, lend itself well to careful measurement or control of humidity, partly because it is affected in a complex way by changes in temperature, and partly because the hair (or other sensitive element, such as a light wooden rod) responds somewhat differently when the humidity is rising than when it is falling--the phenomenon known as hysteresis.

3/ A note to those who are curious about the significance of numerical constants--the constant 0.623 is the ratio of the molecular weights of water vapor and of dry air.

A second method for determining humidity is the direct determination of the dew point of the air as well as its temperature. As the name "dew point" itself indicates, this is accomplished by cooling the air slowly and noting the exact temperature at which dew begins to form on the surface which is cooling it. If the cooling surface is mirror-bright the clouding of the surface by the deposit of dew is a very sensitive indicator, and with proper precautions the dew point temperature can be determined to a small fraction of a degree Fahrenheit. Now it is known that the air has become saturated at that temperature; from Table 1 (or a similar more complete table at closer temperature intervals[4/]) the vapor pressure of water at this temperature is found; this is equal to the partial pressure of water vapor in the original sample of air. If the barometric pressure is known, the absolute humidity can be calculated by using equation 2. If the temperature of the original sample of air is known, its relative humidity can be calculated by using equation 1, the vapor pressure of water at the air temperature being also found in Table 1. Thus, for example, suppose the air temperature is 80° F., the barometric pressure is 29.00 inches, and the dew point is found to be 60° F.; Table 1 shows that the partial pressure of water vapor in the air is 0.522 inches of mercury, and the vapor pressure of water at 80° F. is 1.032 inches. Then from equation 1 the relative humidity is 50.5 percent, and from equation 2 the absolute humidity is 0.0114 pounds of water vapor per pound of dry air.

Dew point measurement has not come into use in ordinary dehydrator operation, probably because wet-bulb thermometry, which will be described in the following paragraph, requires less elaborate equipment and seems easier for unskilled persons to use. No automatic humidity control instrument based upon dew point measurement has been developed commercially, although there is an instrument on the market which will indicate automatically the dew point of a sample of gas introduced into it, formation of the cloud on the cooled mirror surface being sensed by a photoelectric cell. This instrument has been used to measure the small amount of water vapor in compressed cylinder bases, an application which suggests that dew point measurement may be useful in following the very low absolute humidities encountered in dehumidified air such as may be used in finishing bins or in packaging rooms.

The method known as wet-bulb thermometry has been almost universally used for controlling dehydrator operations, in spite of several well known limitations and drawbacks. It depends upon the observed fact that when a moist object is exposed to a current of air, the evaporation of water from the object cools both the air flowing past it and the object itself. The drier the air, the greater will be the amount of cooling. If the air is saturated with water vapor, no evaporation will take place and no cooling will occur.

[4/] See, for example, tables in the publication by Goff and Gratch, footnote, page 4.

The principle is applied by exposing two similar thermometers to the air stream, the sensitive bulb of one of them being kept constantly moist with water. The temperature indicated by the latter is known as the wet-bulb temperature of the air stream, while the temperature shown by the other, actually the temperature of the air as ordinarily measured, is distinguished for this purpose by calling it the dry-bulb temperature. The difference between the two temperatures is commonly known as the wet-bulb depression. At any given temperature, the greater the wet-bulb depression the lower the humidity of the air. If the wet-bulb depression is zero, the air is saturated with water vapor. Wet-bulb depressions of as much as 100° F. are encountered in some commercial dehydrators.

Wet-bulb thermometry was placed upon a sound basis many years ago, mainly through the efforts of meteorologists who needed a convenient and reasonably accurate method of measuring atmospheric humidity as a part of their weather observations. Relationships established by these investigators between percent relative humidity and dry-bulb temperature, wet-bulb temperature, barometric pressure, and air velocity past the thermometers are still the basis of present humidity tables and charts, although their experimental work was confined almost wholly to temperatures below 120° F.

Three important precautions must be observed if the wet-bulb thermometer is to indicate the true wet-bulb temperature. In the first place, its sensitive bulb must be kept continuously moist with pure water. This condition is not easy to meet, particularly if the instrument is to be kept continuously in service as a humidity indicator or controller in a dehydrator. The moist surface is usually secured by encasing the bulb in a fabric or porous ceramic sheath and causing the latter to act as a wick from a water reservoir. The wick itself should be exposed fully to the air stream, so that the water reaching the sheath around the bulb will have come very nearly to the wet-bulb temperature. An actual stream of water running over the bulb or through the sheath is, of course, unacceptable. Maintenance of the wick in good condition is difficult. If it is supplied with ordinary tap water it will quickly fill with lime salts and cease to act as a wick; distilled water supplied to the reservoir will eliminate this trouble. If the circulating air is dusty, however, as it is to some extent in all dehydrators, the wick will gradually cake up and become inoperative. Frequent inspection and replacement of wicks is the only cure.

The second precaution is that the thermometers must be so located as to minimize radiation effects. This means that if one places his eye where the thermometer bulbs are to be located he should not be able to see from there any surfaces within the dehydrator that are likely to be very much hotter or very much colder than the circulating air itself. Since the controlling thermometers for a dehydrator are usually located at the "hot end" the most important practical precaution is that they be placed so that they cannot "see" the furnace or the steam coils which supply heat to the circulating air.

Finally, the wet-bulb thermometer must be placed in an air stream of sufficient velocity. Fortunately, investigations have shown that while an increase in air velocity increases the cooling effect on a moist object, further change is small after a velocity of about 1000 feet per minute is reached. Standard humidity tables and charts are based upon measurements made in air currents of at least that velocity, and badly erroneous conclusions may be drawn from readings of a wet-bulb thermometer which is exposed to a much slower air stream. Wet- and dry-bulb sets are, it is true, sold for use in homes where there is only slight and variable air movement past the wet bulb, but these instruments are especially calibrated for low air velocity and are not expected to maintain any considerable degree of accuracy. Proper location of the wet bulb in a commercial dehydrator is, actually, a rather difficult design problem. One expedient that has been used is to aspirate air from the main air stream past the thermometer bulbs by means of a small motor driven exhaust fan, which discharges back into the air stream.

One very simple form of the wet- and dry-bulb thermometer set is almost indispensable to the dehydrator operator who wishes to exercise good control of his operations. This is the "sling psychrometer", illustrated in Figure 2. It is the instrument used routinely by Weather Bureau observers to measure atmospheric humidity. The two identical thermometers are carried in a light frame which swivels on a handle so that the thermometers can easily be whirled by hand. One of the thermometers, projecting from the frame a little farther than the other has its bulb covered by a light braided cotton sheath, which is dipped in water before the measurement is made. The observer whirls the thermometers for 10 seconds or so, makes a quick reading of the wet-bulb thermometer, whirls the set again for several more seconds, reads again, and continues until the wet-bulb reading is constant. Then he reads both thermometers quickly and carefully.

The sling psychrometer can be used not only to determine that very important datum, the absolute humidity of the fresh air supply to the dehydrator, but also, in cases where a man can safely stay for a few minutes inside a dehydrator while it is in operation, can be used to check the accuracy of fixed or control instruments. When its readings are combined with those of a barometer (a good temperature-compensated aneroid barometer is adequate), the actual dehydration conditions can be checked with ample precision for practical purposes.

Automatic wet-bulb temperature control instruments are available commercially. They have been applied to the control of humidity in dehydrators by the operation of direct steam humidifying jets, water dehumidifying sprays, or the control of recirculation dampers. Precautions in the location of the sensitive bulb and the effective maintenance of a moist surface must be carefully observed if the instrument is to be effective. The wick used to provide the wet surface poses a difficult problem if the bulb is, as usual, located in the air stream at the hot end of the dehydrator, for it must supply water rapidly under the excellent drying conditions that prevail there, and yet it should not be

FIGURE 2 — SLING PSYCHROMETER

so thick or heavy as to add unduly to the time-lag of the sensitive bulb in following changes in the true wet-bulb temperature of the air. Since the wet-bulb temperature in the common type of tunnel dehydrator is practically the same at both ends of the tunnel, less trouble will be experienced but the same information will be obtained if the sensitive bulb is located in the air stream at the cool end, where evaporation will be much slower.

While wet-bulb thermometry was developed as a technique for measuring the relative humidity of air, the actual wet-bulb and dry-bulb temperatures themselves have attained in practice an independent importance. Directions or specifications for the dehydration of fruits and vegetables are now generally written in terms of these temperatures, not in terms of humidities. From the standpoint of the dehydrator operator, of course, there is a great gain in simplicity if he can use the readings of his instruments directly. However, the calculations of a dehydrator designer, or such estimates as an operator may wish to make of drying capacity or heat requirement, do require that wet- and dry-bulb temperatures be translated at least into terms of absolute humidity. Various forms of tables and charts have been devised to facilitate this translation.

I-F. Humidity Tables and Charts

A measurement of the dew point, the air temperature, and the barometric pressure can, as we have already seen, be readily translated into humidity terms after reference to a table or a chart showing the vapor pressure of water at various temperatures. The equivalent formulae for calculating humidity or dew point from wet- and dry-bulb temperatures are more complicated. Comprehensive tables[5] and various forms of humidity chart have therefore been worked out to simplify the translation.[6] Figure 3

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[5] For example, "Psychrometric Tables", Charles F. Marvin, U. S. Weather Bureau, No. 235 (1941). Such tables, being designed for the use of weather observers, do not carry temperatures up into the usual dehydrator range.

[6] Fan engineering. R. D. Madison, Ed. Buffalo Forge Co., Buffalo, N.Y. 4th Edition, pp. 43-44, 1938.
Low and normal temperature psychrometric charts. W. H. Carrier. Carrier Corp., Syracuse, N. Y. 1940.
Conditioning of gases and air. Staff Report. Chem. Met.Eng. 47(5): 286-299 (1940).
Psychrometric chart for high temperatures. W. H. Carrier. Carrier Corp., Syracuse, N. Y. 1941.
Humidity chart for air and water. H. J. Garber. Reinhold Publ. Corp., New York. 1943.
Air conditioning analysis, with psychrometric charts and tables. Wm. Goodman. Macmillan Co., New York. 1944.
Hitemp psychrometric chart. Industrial Research Service, Dover, N. H. 1944.
Psychrometric tables and charts. O. T. Zimmerman. Industrial Research Service, Dover, N. H. 1945.

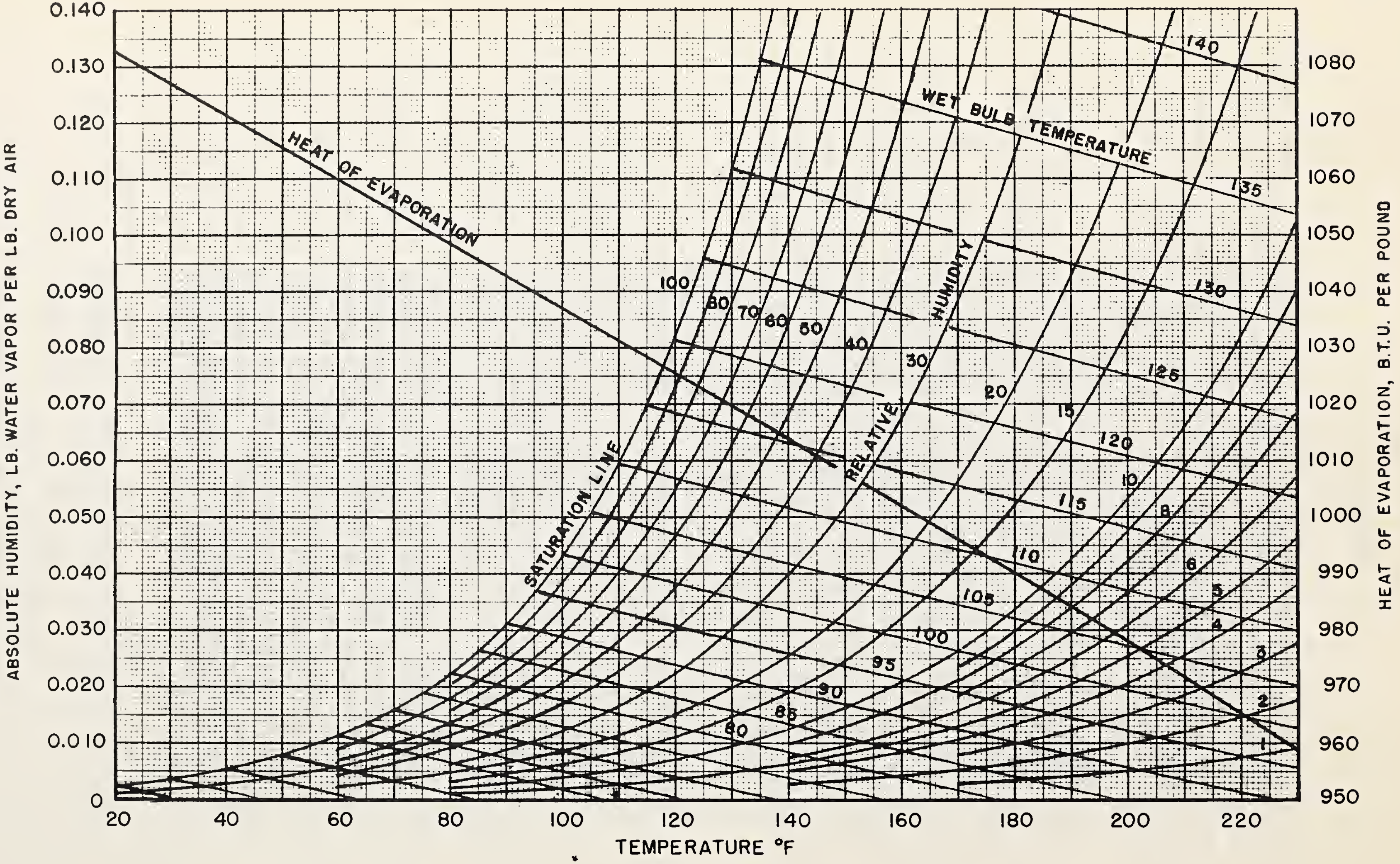

FIGURE 3-HUMIDITY CHART BAROMETER 29.92"

is such a chart, although it cannot be reproduced in this bulletin on a large enough scale to be suitable for precise calculations. In this chart the dry-bulb temperature of the air is plotted along the horizontal axis, the absolute humidity along the vertical axis. The nearly straight oblique lines sloping downward to the right are lines of constant wet-bulb temperature, and the curves rising toward the right are lines of constant relative humidity. It must be emphasized that this chart is strictly valid only at sea-level normal barometric pressure, 29.92 inches of mercury. The corrections that must be applied for differences in barometric pressure will be discussed in the following section of this bulletin. The following examples of the use of the chart are all based on the supposition that the barometer reading is 29.92 inches.

Example 1. What are the absolute humidity and the percent relative humidity when the dry-bulb temperature is 180° F. and the wet-bulb temperature 100° F.? The intersection of these two lines on the chart falls at an absolute humidity of 0.0237 pounds of water vapor per pound of dry air and at 7.2 percent relative humidity.

Example 2. What wet-bulb temperature will correspond to a 65 percent relative humidity in the exhaust air from a dehydrator, the dry-bulb temperature being 120° F.? Reading directly from the chart, the wet-bulb temperature will be 107° F.

Note that if air is warmed or cooled without any change in the amount of water vapor it contains, its absolute humidity, by definition, remains constant. Since the dew point of air is determined by cooling it and noting the temperature at which saturation occurs, the dew point can evidently be determined on the chart for air of a given absolute humidity by moving horizontally to the left and noting the temperature of intersection with the saturation curve, which is marked 100 percent relative humidity.

Example 3. What is the dew point of the air specified by the conditions of Example 2? From the chart, at a temperature of 120° and 65 percent relative humidity the absolute humidity is 0.0505 pound of water vapor per pound of dry air. Following horizontally, the intersection of this absolute humidity with the saturation curve comes at a temperature of 105° F., which is the dew point.

It may be well to remind the reader at this point that of the three kinds of temperature we have been discussing, the dry-bulb temperature is always the highest, the wet-bulb temperature is intermediate, and the dew point temperature is always the lowest. Thus, in the preceding example, dry-bulb temperature is 120°, wet-bulb temperature is 107°, and dew point temperature is 105°.

I-G. Effect of Atmospheric Pressure on Humidity Measurements

Figure 3, like all published humidity charts, is calculated for normal sea-level barometric pressure. But it is safe to say that no commercial dehydration plant is located at sea level; indeed, some of the important dehydration areas in the United States lie at an altitude of more than 6000 feet, where the normal barometric pressure will be, perhaps, only 23 or 24 inches of mercury instead of nearly 30 inches. Figure 4 gives the approximate mean barometer reading at altitudes up to 8,000 feet. In addition to this predictable effect of altitude, however, the barometric pressure at any location fluctuates from day to day with changes in the weather, within a range of as much as 1 to 2 inches of mercury, or occasionally even more.

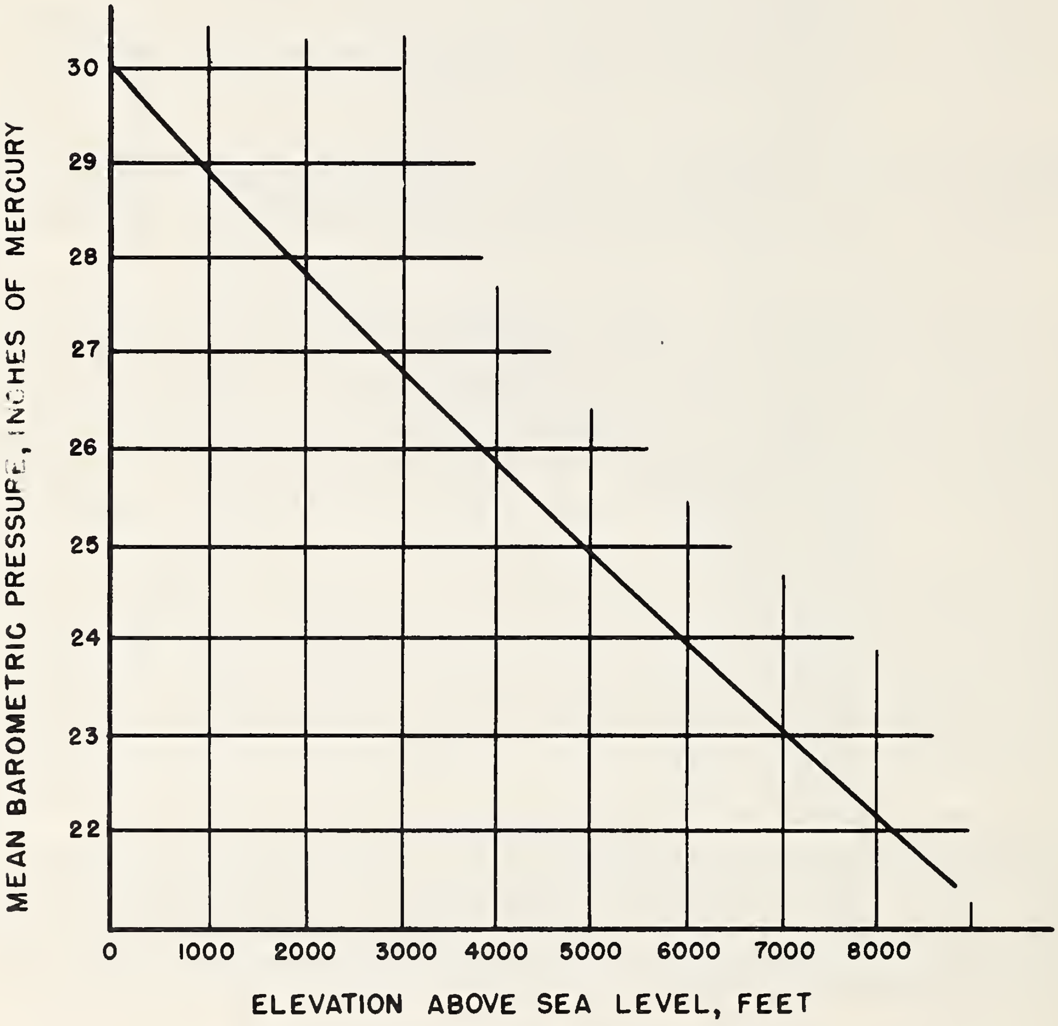

FIGURE 4 - APPROXIMATE RELATION OF BAROMETRIC PRESSURE TO ALTITUDE

The error resulting from use of the standard humidity chart without correction for barometric difference may be substantial, particularly in the estimation of absolute humidity. For example, if wet- and dry-bulb temperature readings of 120° and 170° respectively are taken in a dehydrator at a location where the barometer reads only 23.92 inches of mercury, reference to the standard humidity chart gives an absolute humidity of 0.0680 pounds of water vapor per pound of dry air, whereas the true value is 0.0914, almost 35 percent greater. The error in estimation of dew point and percent relative humidity will be less serious.

Some published humidity charts[7] are accompanied by tables of correction factors which can be applied to readings from the standard charts to obtain true humidities at other barometric pressures than the standard. The correction process is somewhat laborious if many calculations are to be made. If the technologist in a dehydration plant intends to make a serious study of his dehydrators, he will find it worth his while to construct a humidity chart on a large scale for his own use, basing it upon the mean barometric pressure at his location. Day-to-day fluctuations of the barometer will cause smaller errors in his estimates, and if precision is wanted the necessary corrections can be approximated by a relatively simple formula.

The first step in construction of such a chart, having set up the scales of dry-bulb temperature and absolute humidity as coordinates, is to locate enough points on the saturation line (100 percent relative humidity) so that a smooth curve can be drawn through them. This can be accomplished by calculation from equation 3 (page 10) and the table of vapor pressures, Table 1 (page 5). For example, if the chart is to be constructed for a barometric pressure of 25.50 inches, the point on the saturation curve corresponding to a temperature of 120° (vapor pressure from Table 1 = 3.45 inches) is calculated from equation 3 as follows:

$$a_s = \frac{0.623 \times 3.45 \times 100}{100 \times 25.50 - 3.45 \times 100} = 0.0975 \text{ lb. water vapor per lb. dry air.}$$

Next, equation 3 is used to locate points on a sufficient number of other relative humidity curves. For example, the point on the 50 percent relative humidity curve corresponding to a temperature of 120° is calculated as follows:

$$a = \frac{0.623 \times 3.45 \times 50}{100 \times 25.50 - 3.45 \times 50} = 0.0452 \text{ lb. water vapor per lb. dry air.}$$

Plotting of the wet-bulb temperature lines on the chart requires the use of a new equation which contains as one of its terms the latent heat of

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[7] For example, "Psychrometric Chart for High Temperatures", W. H. Carrier. Carrier Corp., Syracuse, N. Y. 1941.

evaporation of water at the given wet-bulb temperature. The latent heat of evaporation is a measure of the quantity of energy that is carried out of the liquid by the fast-moving molecules when unit weight, such as a pound, evaporates. In engineering work it is expressed in B.t.u.[8] per pound. Its value varies with the temperature at which evaporation takes place, as shown by the special curve plotted in Figure 3 (page 16).

The formula required is as follows:

$$a = \frac{H_w a_s - 0.24\ (t - t_w)}{H_w + 0.47\ (t - t_w)}\ .\ ^{9/} \quad - - - - - - \quad (5)$$

The symbols have the following significance:

a = absolute humidity at a point on the desired wet-bulb temperature curve where the dry-bulb temperature is t.
a_s = absolute humidity at the point of intersection of the desired wet-bulb temperature curve with the saturation line.
H_w = latent heat of evaporation of water at the given wet-bulb temperature, t_w.

The value of a_s will already have been determined; in the above example it was found to be 0.0975. From Figure 3 the value of H_w is found to be 1026 B.t.u. per pound. Now suppose that a point on the new 120° wet-bulb temperature curve is to be established at a dry-bulb temperature of 220°:

$$a = \frac{1026 \times 0.0975 - 0.24\ (220 - 120)}{1026 + 0.47\ (220 - 120)} = 0.0708.$$

This gives two points on the required line, since we already have its end point at a_s. Fortunately, the wet-bulb temperature lines are only slightly curved. One more calculation, say at t = 170°, will enable a good smooth curve to be drawn accurately. Then if similar wet-bulb temperature lines are established at about 5-degree intervals, the intermediate lines at 1-degree intervals can be drawn by careful interpolation.

SPECIAL NOTE: In all of the remaining numerical examples given in this bulletin, normal sea-level barometric pressure is assumed unless otherwise specifically stated.

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[8] The British thermal unit is the quantity of heat required to raise the temperature of one pound of water 1° F.

[9] In this equation 0.24 is the specific heat of dry air and 0.47 is the mean specific heat of water vapor in the usual range of dehydrator temperatures.

I-H. Volume of Mixtures of Air and Water Vapor

The volume, expressed in cubic feet, occupied by one pound weight of any gas or vapor is known as its specific volume. For example, the specific volume of dry air at normal sea-level pressure and a temperature of 160° F. is 15.62 cubic feet per pound. Water vapor is lighter than air; a pound of it will occupy about 60 percent greater volume than a pound of air if the two are measured at the same temperatures and pressures. Moist air is therefore a little lighter than dry air.

Any gas or vapor will expand and occupy more volume per pound if its temperature is raised or if the pressure on it is decreased. The relation of specific volume to temperature and pressure is very simple:

1. Specific volume is directly proportional to the absolute temperature (that is, temperature measured from the "absolute zero", or temperature, ° F. + 459.6°).

2. Specific volume is inversely proportional to the pressure.

A mixture of air and water vapor, that is moist air, behaves in this respect in the same way as dry air does, so long as the change in temperature or pressure does not bring about saturation and the condensation of part of the water vapor.

The dehydration technologist will not often have occasion to use the specific volume of dry air, but for several reasons he should be able to determine or calculate the specific volume of warm, moist air such as will be circulating in the dehydrator. For example, estimation of the weight of air moving through the dehydrator, needed for calculations of evaporative capacity and heat economy, can be done most readily by determining the volume of air flow, either by making an air velocity survey or by knowledge of the fan characteristics, and then translating from volume terms to weight terms.

A useful concept for this purpose is the humid volume, defined as the volume (in cubic feet) of moist air per pound of dry air. The somewhat peculiar mixture of terms has the same advantage as the concept of absolute humidity, namely that it has an unchanging base (the pound of dry air) which is not affected by the changes in pressure or temperature which occur in the dehydrator. Tabulation or charting of this quantity would be too complex for inclusion in this bulletin; its value can be estimated with sufficient precision from the following formula: 10/

$$v = (0.0253 + 0.0405a)\,(t + 459.6)\,\frac{29.92}{B} \quad . \; - \; - \; - \; - \quad (6)$$

10/ In this formula the barometric pressure, B, means the pressure at the particular location which is of interest. Since the pressure inside the dehydrator itself is generally different from the pressure outside where the barometer is located, readings of the latter may be corrected, if great precision is required, by adding or subtracting the pressure difference between the air in the dehydrator and the outside air. If the pressure in the dehydrator is indicated, as is usual, by a water manometer, the pressure shown by the latter, in inches of water, can be converted to inches of mercury by dividing by 13.6.

As an example, what is the humid volume of the moist air at the hot end of a dehydrator where the temperature is 170° F., the absolute humidity has been found to be 0.0520, and the barometer reading is 25.76 inches? From equation 6,

$$v = (0.0253 + 0.0405 \times 0.0520)(170 + 459.6)\,\frac{29.92}{25.76} = 20.1 \text{ cubic feet of moist air per lb. of dry air.}$$

For a fairly wide range of operating conditions, in fact, the humid volume of the air in the dehydrator will be found to be between 15 and 20 cubic feet per pound. Very rough calculations of drying capacity are frequently made on the assumption, good enough for rule of thumb purposes, that the humid volume is 16 cubic feet per pound. Even though he may find such approximations useful, however, the technologist should not overlook the marked effects that changes in humid volume, particularly those that result from low barometric pressure, will have on the operation of the dehydration plant. Centrifugal fans and boiler furnaces, in particular, will be affected.

I-I. Specific Heat of Air-Water Vapor Mixtures

The specific heat of any substance is substantially equal (although the term is not properly defined this way) to the quantity of heat, in B.t.u., required to raise the temperature of 1 pound of it 1° F. The specific heat of dry air in the usual range of dehydrator temperatures is 0.24. That is, 0.24 B.t.u. applied to 1 pound of dry air will raise its temperature 1°. The specific heat of pure water vapor in this temperature range is about 0.47.

The humid heat of air containing water vapor is defined, analogously to humid volume, as the quantity of heat required to raise the temperature of 1 pound of dry air, plus whatever water vapor accompanies it, 1° F. If the absolute humidity is known it may be calculated by the following formula:

$$\text{Humid Heat} = 0.24 + 0.47\,a \quad . \; - - - - - - - \quad (7)$$

Example: 1570 pounds per minute of moist air with an absolute humidity of 0.0510 is flowing through a steam coil heater. How much heat must be supplied to this air to raise its temperature 110° F.? The humid heat of the mixture is 0.24 + 0.47 x 0.0510, or 0.264. The weight of dry air flowing is 1570/(1 + 0.0510), or 1492 pounds per minute. The heat required is therefore 1492 x 0.264 x 110, or 43,300 B.t.u. per minute.

I-J. Measurement or Estimation of Air Velocity in the Dehydrator

Perhaps the most difficult and least satisfactory of all the measurements the dehydration technologist may be called upon to make is that of the air velocity in a working dehydrator. The kinds of instrument available for this purpose are few, and all have serious limitations.

The procedure most often used is not a measurement at all, but rather a rough estimate. The size and rate of rotation of the circulating fan being known, and the static pressure drop across the fan being determined by use of a manometer, the volume discharge of the fan is estimated by reference to the characteristic curves furnished by the manufacturer. If the air velocity across the surface of drying trays in the dehydrator is wanted, it is calculated by dividing this estimated total air flow by the free cross-sectional area of the dehydrator (that is, the total cross-section area of the spaces between loaded trays, and around the trucks, through which air can flow). The result is, of course, uncertain for several reasons. One is that individual fans do vary from the standard characteristics of their type. Another, and sometimes appreciable, error is that no account is taken of leakage from the dehydrator. The most serious rises from the implicit assumption that the air flow divides itself uniformly through all of the free openings in the cross section of the dehydrator, whereas much of it may short-circuit uselessly beneath or around the trucks. Nevertheless, this kind of estimate gives at least the order of magnitude of the air velocity; it is better than no estimate at all.

The instrument that has been most commonly used for making actual measurements of air velocity in dehydrators is the windmill anemometer.[11] It is, in fact, a small, very light windmill, mounted in a case which carries dials to record the number of revolutions. The air velocity is obtained from a calibration curve, relating velocity to the number of revolutions of the windmill counted in a fixed length of time, such as a minute.

Such an anemometer can furnish a reasonably good measurement of the total air flow through a large dehydrator if it is used to make a velocity traverse of an unoccupied section of the dehydrator. That is, the cross-section of the passage through which air is flowing is divided into zones, or cells, and a velocity measurement is made in each, total air flow being obtained by summing those velocities and the corresponding cross-sectional areas. The instrument itself is too large to be placed in the narrow air channel between drying trays; velocity across the trays, as calculated from the total air flow, must be a rough approximation. Another serious drawback of the instrument is obvious. A human operator must remain within the dehydrator to position the instrument (he must remain as far as possible from the instrument in order to avoid the creation of eddies which would falsify its readings) and to make the

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[11] These instruments are illustrated in the catalogs of most scientific instrument supply companies.

timed readings. Measurements of this kind made in a cold dehydrator have, however, provided highly instructive evidence of faulty distribution of air flow within the equipment and have thus helped materially to straighten out the idiosyncrasies which each individual dehydrator displays.

Two other types of commercially available instrument may find application in dehydrator work. One which is used widely in the installation of air conditioning systems comprises a case within which a very light swinging vane is exposed to the air stream admitted by an opening in the side of the case, to which an extension tube may also be attached. An indicator hand on the dial of the instrument is actuated by the swinging vane, and the scale may be read directly in terms of air velocity. An instrument of this kind is especially suitable for measuring air flow in ducts or in front of ventilation registers. Like the windmill anemometer, it must be used with caution in a location where the observer's body itself will cause a disturbance of the air stream.

The other instrument referred to above is the hot-wire anemometer. A length of fine wire, slightly heated by an electric current, is exposed to the air stream. The temperature attained by the wire, which depends on the velocity of the air flowing past it, affects the electrical resistance of the wire. This change in resistance is measured by a meter calibrated in terms of air velocity. An instrument of this type is not much affected by the direction of the air flow past it, while the windmill anemometer and more especially the swinging-vane anemometer give full readings only if they are positioned to face directly into the air stream.

An instrument known as a heated-thermocouple anemometer, originally described by Hukill[12] and further developed by Lowe and Hawes[13], offers the possibility of more satisfactory air velocity measurements in dehydrators, although apparently it has not yet been applied for that purpose. Lowe and his co-workers at the Western Regional Research Laboratory have, however, used these anemometers to make comprehensive air velocity surveys in a rather similar kind of equipment, namely a commercial food freezing tunnel. The instrument comprises a pair of fine wire thermocouples, mounted side by side on a small fixture which can be positioned in the air stream (even in the narrow clearance between two trays); one of the thermocouples is heated slightly by a known electric current flowing through a fine resistance wire wrapped around it. The difference between the temperatures of the two couples, indicated by an electrical instrument which can be at a distance, depends in a definite manner upon the velocity of the air stream.

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[12] W. V. Hukill. An anemometer for measuring low air velocities. Refrig. Engin. 28:197 (1934).

[13] E. Lowe and J. R. Hawes. An improved heated-thermocouple anemometer for use in air-blast freezers. Food Tech. 3(7):241-243, July 1949.

Some writers on dehydration mean by the term "air velocity in the dehydrator" simply the quotient of volume of air flowing, in cubic feet per minute, divided by the gross inside cross-sectional area of the dehydrator, in square feet; this would be essentially the same as the air velocity determined by anemometer in an unoccupied section of a tunnel. The air velocity term to which drying rates are directly related is, however, the actual velocity past the wet material. Since trucks, trays, and their load occupy a substantial volume in the tunnel, the velocity of air across the material in a well designed dehydrator will be higher than the velocity in an unoccupied section. References to air velocity in this bulletin will always signify the velocity past the drying material, measured or estimated as well as may be possible.

II. CHARACTERISTICS OF EVAPORATION FROM A MOIST SOLID

This chapter considers in detail the manner in which moisture evaporates from a moist solid, considering first the surface evaporation and then the transfer from the interior of the solid. The equilibrium between a moist solid and moist air is discussed. Such consequences of drying as shrinkage of volume and migration of sugars are described.

II-A. Specification of the Moisture Content

Analytical determinations of the amount of moisture in a vegetable are customarily expressed in percentage by weight. For example, the analysis of a sample of blanched potato dice may be given as 80 percent moisture--that is, in 100 grams of sample there are 80 grams of water and 20 grams of "bone-dry" matter.

An alternative way of expressing moisture content has been found to make many dehydrator calculations much simpler. This is the ratio of the weight of water in a sample to the weight of dry matter. In the foregoing example this ratio is 80/20, or 4.0.[1] If the analysis of a sample of dehydrated potato dice gives 6.5 percent moisture, the "dry basis" moisture content will be 6.5/(100 - 6.5), or 0.0695 pounds of water per pound of dry solids.

This "dry basis" manner of expression is advantageous in dehydrator calculations for the same kind of reason as that responsible for the choice of absolute humidity in dealing with the air conditions. The weight of dry matter in a particular lot of material advancing through a dehydrator remains constant from the beginning to the end of the process, and thus provides an unchanging base for the calculations.

If the moisture contents both of the fresh material entering the drier and of the product leaving the drier are known, the drying ratio, or its reciprocal, the drying yield, can be calculated. The formulas may contain either "percent moisture" (wet basis) or moisture content (dry basis):

$$\text{Drying ratio} = \frac{\text{Weight entering drier}}{\text{Weight leaving drier}} = \frac{100 - M_f}{100 - M_o} = \frac{T_o + 1}{T_f + 1}, \quad - - \quad (8)$$

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[1] Moisture content calculated this way "on the dry basis" can be, and sometimes is, also expressed as a percentage; in the example the result would be 400 percent. In order to avoid confusion between the two different ways of expressing moisture content, however, the "dry basis" moisture content will always be expressed in this bulletin as the ratio itself, not as percentage, and will usually be further identified by the expression "pounds of water per pound of dry solids". Some writers call it the "moisture ratio".

where M_o is moisture content (wet basis, percent) in the material entering the drier, M_f is moisture content (wet basis, percent) in the product leaving the drier, and T_o and T_f are the equivalent expressions on the dry basis, pounds of moisture per pound of dry solids. The drying yield is the reciprocal of either of the formulas given above.

Suppose, for example, that carrot dice enter a drier containing 89 percent moisture, and leave it containing 5 percent moisture. Then

$$M_o = 89,\ M_f = 5,\ T_o = 89/11 = 8.09,\ T_f = 5/95 = 0.053.$$

$$\text{Drying ratio} = \frac{100 - 5}{100 - 89} = \frac{8.09 + 1}{0.053 + 1} = 8.63.$$

$$\text{Drying yield} = \frac{100 - 89}{100 - 5} = \frac{0.053 + 1}{8.09 + 1} = \frac{1}{8.63} = 0.116 = 11.6 \text{ percent.}$$

The drying ratio and drying yield do not express the total shrinkage in weight of product in passing through the plant. The over-all ratio between weight of raw material entering the plant and weight of finished product leaving it must also take into account the losses, sometimes large, during preparation and final inspection.

The weight of water to be evaporated from the material is, of course, $T_o - T_f$ pounds of water per pound of bone-dry solids. Then the evaporation per pound of material entering the drier is $\frac{T_o - T_f}{T_o + 1}$, and the evaporation per pound of material leaving the drier is $\frac{T_o - T_f}{T_f + 1}$. These quantities may also be calculated as $\frac{M_o - M_f}{100 - M_f}$ and $\frac{M_o - M_f}{100 - M_o}$, respectively. For the example given above the weight of water to be evaporated is $8.09 - 0.053 = 8.037$ pounds of water per pound of bone-dry solids, or $8.037/9.09 = 0.884$ pounds of water per pound of carrot dice entering the drier, or $8.037/1.053 = 7.63$ pounds of water per pound of dried carrot dice leaving the drier.

It is easy to see now the truth of the following important, if somewhat paradoxical, statement: Most of the water is evaporated from a vegetable while it is still very wet. The moisture content of fresh vegetables is high; T, the dry-basis moisture content, ranges from 3 or 4 to as much as 25. For the carrot dice in the above example, $T_o = 8.09$, a typical moisture content for that vegetable. If 90 percent of the water is evaporated from a sample of this material, 0.809 pounds of water still remain per pound of dry solids, so the partly dried dice at this stage will still contain $0.809 \times 100/(1 + 0.809)$, or almost 45 percent moisture. Removal of 99 percent of the water would leave a product still containing 7.5 percent moisture.

The principle discussed in the foregoing paragraph has been applied by workers[2] at the Western Regional Research Laboratory as the basis of a novel method of food processing called dehydrofreezing. When the weight of a vegetable like green peas or a fruit like apples is reduced about one-half by dehydration, the remaining moisture content is still high, and the produce retains most of its fresh characteristics. If it is then frozen to preserve this freshness, not only are freezing and shipping costs less than for the frozen fresh fruit or vegetable, but the shrinkage in volume also reduces packaging and storage costs.

II-B. Evaporation from the Surface Layers of a Wet Material

When first exposed to a stream of air, cut pieces of a vegetable act essentially like a fine-grained sponge full of water. The moisture in the surface layers evaporates very rapidly.

Evaporation from a water surface has been studied by many investigators, and the factors which govern its rate are well understood. The observed relations are to a large extent explainable on the assumption that a stagnant film of nearly saturated air persists at the surface. Air flowing past the surface tears away the outer layer of the film, which is replenished by evaporation of more water. The more rapid the flow of air, the thinner the film becomes, and the more rapid the transfer of water vapor into the air stream.

It should be apparent that, during this early stage of drying, the wet material acts exactly like the moist wick of a wet-bulb thermometer. Experiment confirms the result that might be expected; the temperature of the wet material quickly comes to the wet-bulb temperature of the air stream.[3] The results of an experiment at the Western Regional Research Laboratory are pictured in Figure 5. A fine thermocouple was buried in a carrot slice 3/16 inch thick, and the temperature of the slice and the wet- and dry-bulb temperatures of the air were recorded during a dehydration run in which these air temperatures were changed substantially during the run. In the figure the temperatures are plotted vertically, the moisture content horizontally with the scale reversed, to correspond in direction with the decrease in moisture content as the run progresses. Piece-temperature rose rapidly to the

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[2] L. B. Howard and H. Campbell. Dehydrofreezing--new way of preserving food. Food Ind. 18(5):674-676, May 1946.
R. R. Legault and W. F. Talburt. Quality retention through dehydrofreezing. Refrig. Engin. 57(12):1175-1177, Dec. 1949.

[3] This is strictly true only if the material is suspended in the air stream and is shielded from radiation. If it rests on a tray, conduction of heat from the tray will raise its temperature somewhat. In a drier where heat is mainly supplied to the material by radiation, as in an infra-red drier, the temperature of the moist material may be much above the wet-bulb temperature.

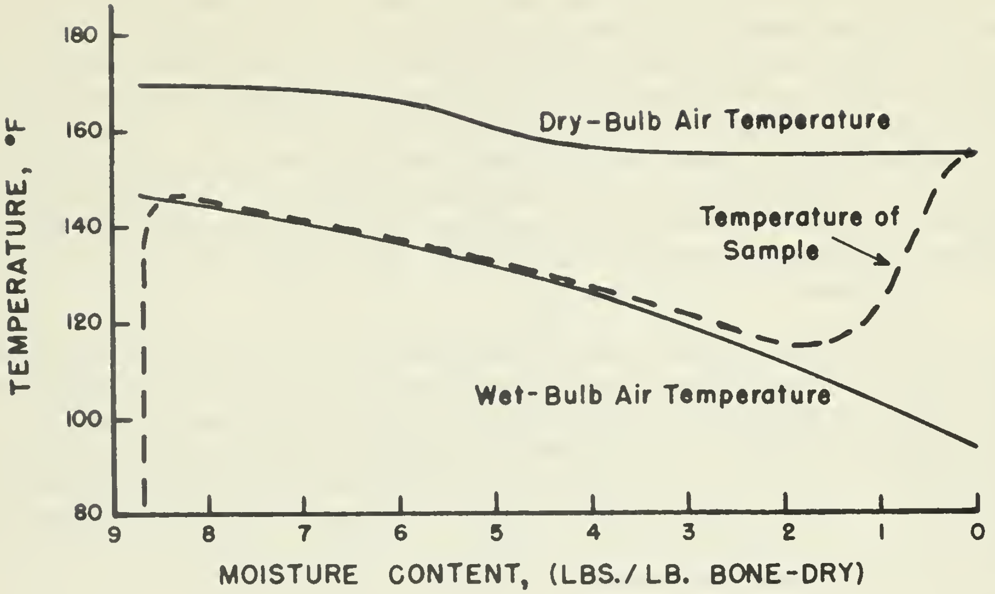

FIGURE 5-RELATION OF TEMPERATURE OF MATERIAL TO TEMPERATURE OF AIR

wet-bulb temperature, and then reproduced that temperature closely while about half of the total water was being evaporated. After that it began to rise, and as the piece approached dryness its temperature nearly coincided with the dry-bulb temperature of the air.

Measurements of the rate of evaporation from wet surfaces have been made by many investigators. Correlation of their results[4] shows that the rate is determined by the rate at which heat is supplied to the wet material (whether from the air alone or also by radiation and conduction from the support), the air velocity, and the difference between the vapor pressure of water from the material at its surface temperature and the partial pressure of water vapor in the air. Shepherd and his associates present a diagram from which the evaporation rate can be estimated for known conditions. For example, at an air flow of 600 feet per minute, dry-bulb temperature 180°, and wet-bulb temperature 110°, Shepherd's diagram indicates a rate of evaporation, for conditions where radiation and conduction of heat are unimportant, of 0.44 pounds of water per hour per square foot of tray surface. For comparison, the British investigators A. J. Ede and K. C. Hales[5] report that the initial

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[4] C. B. Shepherd, C. Hadlock, and R. C. Brewer. Drying materials in trays: Evaporation of surface moisture. Ind. Eng. Chem. 30(4):388-397 (1938).

[5] The physics of drying in heated air, with particular reference to fruit and vegetables. Dept. Sci. and Indus. Research, Food Investig. Special Report No. 53, 1948.

drying rates of trays of potato, carrot, beet, rutabaga, and cabbage pieces all fell within the range of 0.018 to 0.022 pounds of water per hour per square foot of tray surface per degree Fahrenheit wet-bulb depression, at an air velocity of 600 feet per minute; for the conditions of the above example that would be from 1.29 to 1.56 pounds of water per hour per square foot of tray surface, or from 3 to 4 times as rapid a rate as indicated by the Shepherd diagram. The difference is, of course, a result of the fact that the cut surfaces of vegetables loaded on a tray expose several times as much moist surface to the air as the tray area.

Measurements of the drying rate of vegetables on trays show that under constant drying conditions the initial rate of evaporation per unit of surface area is sustained with little change during the removal of the first third or half of the original moisture content--just about the range within which the piece temperature follows the wet-bulb temperature closely. This observation coincides with a well known behavior of nearly all wet materials during drying--at least a part of the water is evaporated at a constant rate.

Note, however, that this constant rate of evaporation is a rate per unit of moist surface. Vegetable pieces start shrinking both in volume and in surface area as soon as they start drying. If the rate of drying is followed only by periodic weighings, as is usual, it will appear to start falling at once, actually because the drying surface is becoming smaller.[6/]

II-C. Removal of Water from Deeper Layers

Evaporation from the surface cannot proceed far before the surface layers of the piece will become drier than those beneath them. If there are communicating pore spaces in the piece, the surface may be supplied with moisture for a while by capillarity from the interior, like a wick whose reservoir has gone nearly dry. But when capillary transfer stops, the rest of the internal moisture must reach the surface by diffusion, and this process must continue during all of the remainder of the drying. It is a complex phenomenon that is still only imperfectly understood, although the rate of diffusion of moisture, more than any other single factor, determines the ease or difficulty of drying products to a low

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[6/] The usual theoretical treatments of the constant-rate phase of drying obviously cannot be of much help in studying practical vegetable dehydration, because there is no feasible way to determine the actual drying area as the drying progresses. A rough approximation to the change in area during the early stages of drying may be made by taking the shrinkage in volume as equal to the volume of water lost, and the shrinkage in area as proportional to the 2/3 power of the shrinkage in volume. It is by such an approximation that data on the drying of vegetables have been analyzed so as to show a constant-rate phase.

moisture content.[7] Roughly, however, the mechanism of diffusion, like that of evaporation, can be pictured in terms of the simile of a crowded dance floor. Suppose that couples of two different nationalities are engaged in the dance, and at the beginning the two nationalities have completely segregated themselves, one at one end of the floor, the other at the other end. At the line of contact between the two crowds, however, the accidents of random shuffling in different directions will occasionally open up a little free space, a "hole", between the dancers of one nationality, and a couple of the other nationality, moving fast enough in the right direction at that time, will slip into it. Repeat this kind of process for a long enough time and the two nationalities will become thoroughly intermingled. Now if some attraction that interests only one of the nationalities is set up outside one end of the dance floor, the reverse process will start to occur. Dancers of that group who happen to be nearby will leave the floor; as others come into the range of attraction they too will leave. After a long enough time, only the one homogeneous group will be left in possession of the floor.

Evaporation of water from the inside of a piece of drying vegetable has some similarity to that picture, but the analogy should not be pushed very far. If the matter were as simple as that, one would expect that the rate at which water molecules would migrate close enough to the surface to evaporate would be proportional to the number of them left behind in the mixture. The rate actually falls off faster than that, as though when the piece approaches dryness the solid molecules begin to hem in the water molecules so they can scarcely move at all. There is considerable evidence[8] that particularly as the moisture content falls below about 20 percent the remaining moisture becomes more and more tightly bound to the solid constituents, so that the rate of diffusion of moisture outwards and the rate of evaporation fall to very low levels. The <u>diffusivity</u> of the moisture in the solid (the unit measures the rate at which moisture will diffuse under standard conditions) may not be more than one-hundredth as great at 10 percent moisture content as at 20 percent.

This behavior is consistent with all we know about the relation of water to nearly dry organic substances such as starch, sugars, pectin, protein, and cellulose. Small amounts of moisture are very firmly adsorbed, as the physical chemists say, in the molecular structure of these substances. The firmness of binding is reflected not only by the

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[7] W. B. Van Arsdel. Approximate diffusion calculations for the falling-rate phase of drying. Chem. Engin. Progress 43(1):13-24 (1947); also as Bureau Circular AIC-152, Western Regional Research Laboratory, Albany, Calif.

[8] Van Arsdel, see reference above.

P. M. Doty, W. H. Aiken, and H. Mark. Water vapor permeability of organic films. Indus. Engin. Chem., Anal. Ed. 16:686-690 (1944).

T. H. Schultz, J. C. Miers, H. S. Owens, and W. D. Maclay. Permeability of pectinate films to water vapor. Jour. Phys. Colloid Chem. 53(9): 1320-1330. Dec. 1949.

low diffusivity of the remaining moisture, but also by a lower moisture vapor pressure than would be exerted by pure water at the same temperature. Numerous measurements of the latter effect have been made by many investigators[9] on nearly all important materials which are dried commercially. B. Makower and G. L. Dehority, of the Western Regional Research Laboratory, and R. Gane, of the Low Temperature Research Station, in England, have published results of measurements of the moisture vapor pressure from dehydrated vegetables.[10] A typical example taken from Makower's results is shown in Figure 6. The moisture content scale on this drawing is reversed in order to emphasize the rapid drop in vapor pressure as dryness is approached.

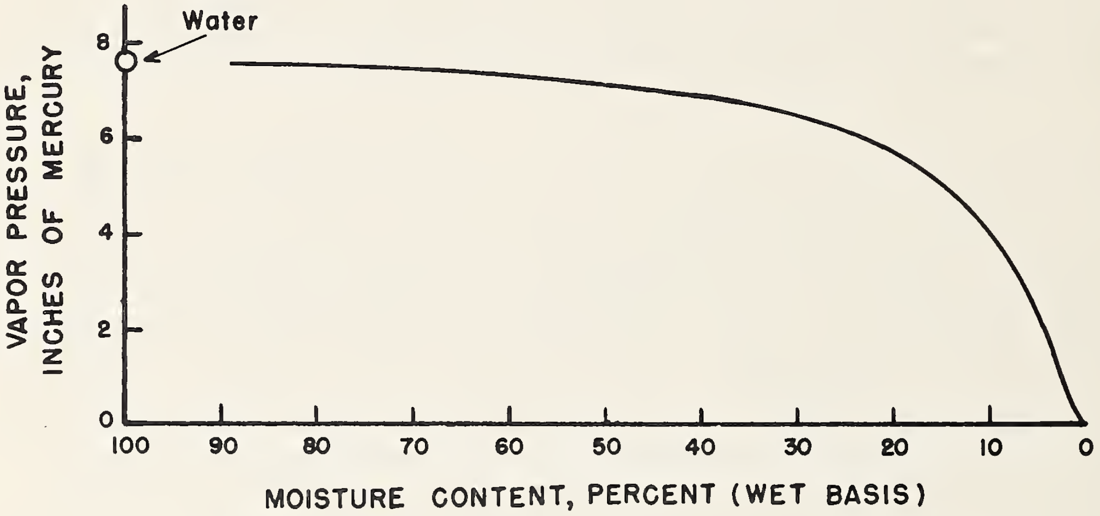

FIGURE 6-VAPOR PRESSURE OF A MOIST VEGETABLE AT 150° F.

Quantitative measurements of the actual diffusion of moisture within a piece of vegetable that is undergoing drying are extremely difficult to make, because of the distortion of the pieces due to shrinkage. The only published results are those of A. J. Ede and K. C. Hales,[11] who dissected

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[9] See Chemical Engineers' Handbook, 3rd Edition, pp. 777-779.

[10] Equilibrium moisture content of dehydrated vegetables. B. Makower and G. L. Dehority. Indus. and Engin. Chem., 35:193-197 (1943).
The water relations of some dried fruits, vegetables, and plant products. R. Gane. J. Sci. Food Agric. 1(2):42-46 (1950).

[11] The physics of drying in heated air, with particular reference to fruit and vegetables. Food Investig. Spl. Report No. 53, Dept. Sci. and Indus. Res., London, 1948, p. 12.

thick slices of potato at various stages of drying, and determined the moisture content in successive layers. Figure 7 is reproduced from their paper. Generally similar pictures of the internal distribution of moisture during drying have been obtained for wood by workers at the Forest Products Laboratory[12] and for soap by two Japanese investigators.[13]

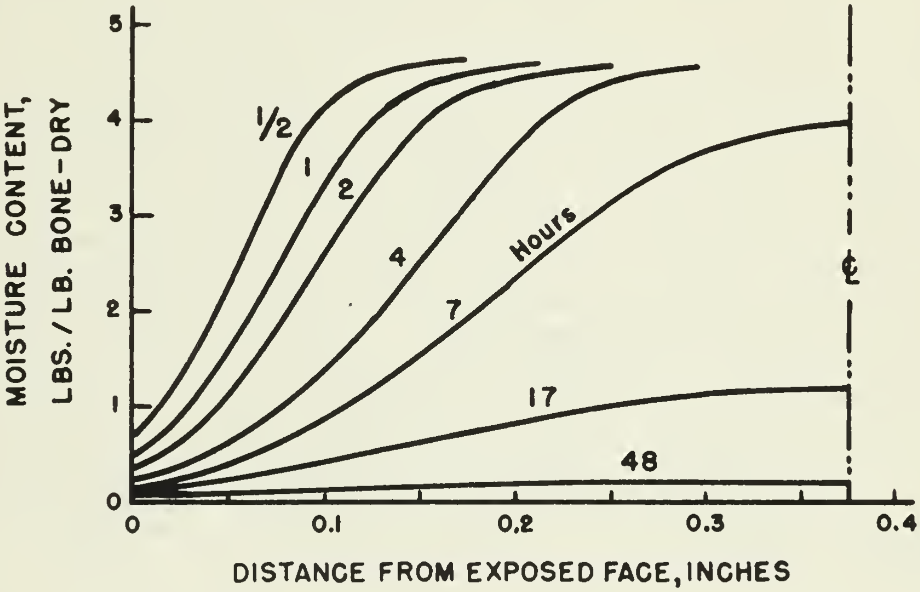

FIGURE 7 - MOISTURE GRADIENTS IN POTATO SLICE DURING DRYING

The form of these moisture distribution curves is consistent with what is known about the laws of diffusion and the change in diffusivity at low moisture contents which was referred to above. Van Arsdel[14] arrived by calculation at moisture distribution curves in the low-moisture range which show the same general characteristics as the experimental curves determined by Ede and Hales.

Calculations of this kind are most readily made if one assumes a kind of rough composite picture of what is going on, forgetting for the moment the mechanism of molecular wandering, and uses instead the simile of the flow of electric current or heat in a conductor. A simple general law for this kind of flow was established long ago. The law states that the flow of electricity (Ohm's law) or heat (Newton's law of cooling) in a

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[12] E. Bateman, J. P. Hohf, and A. J. Stamm, Indus. Engin. Chem., 31:1150-1154 (1939).

[13] S. Kamei and S. Shiomi. J. Soc. Chem. Ind. (Japan), 40:257-263 (1937).

[14] See footnote, page 31.

given system is directly proportional to a "driving force" (electric potential difference or temperature difference) and inversely proportional to a "resistance" (or directly proportional to the reciprocal of resistance, conductance). The conductance, in turn, is directly proportional to a property of the material itself, its electrical or thermal conductivity, directly proportional to the cross-sectional area through which the current is flowing, and inversely proportional to the length of the path. In these terms, the diffusional transfer of moisture across unit cross-sectional area within the moist body is proportional to a characteristic of the material itself, its diffusivity for water, and to a "driving force" which is the difference in concentration of water at two points unit distance apart in the direction of diffusion.[15] This means that, according to this picture, moisture always diffuses from a location where there is more of it to a location where there is less--it tends to equalize its concentration, to bring about a uniform level of moisture content within the piece. But now if moisture is being constantly removed from the surface of the piece by evaporation, the surface is always a little drier than the layer next below it, and that layer a little drier than the next deeper one. A continuous flow of moisture is thus set up from the inside of the piece toward the surfaces as long as evaporation is proceeding at the surface. And as long as drying is taking place, the center of the piece always is more moist than the surfaces. The faster the drying, the more marked this difference between center and surface must be, because only so can a high enough difference in moisture concentration be set up to keep the surface supplied with moisture at a high rate.

"Wet centers" are not, therefore, a puzzling accident in dehydration operation, but a normal accompaniment of rapid drying. The shape of the curves in Figure 7 and the rapid increase in time required to produce a given amount of further drying, are both reflections of a fact referred to above--that the diffusivity for moisture in these materials is not by any means a constant, but instead decreases greatly as the moisture content falls. This behavior is in sharp contrast to that of electrical conductivity and heat conductivity, which change so little with a change in conditions that for ordinary calculations both are usually taken to be true constant characteristics of the material.

The internal redistribution of moisture within a wet material which is granular or which contains communicating pore spaces follows quite

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[15] This kind of definition can be useful only if the moist substance is uniform in temperature throughout, because it infers that no diffusion can take place if there is no difference in the moisture concentrations at two locations in the body, while on the contrary experiments have shown that a transfer of moisture occurs if there is a temperature difference between two locations, even if the moisture concentrations are identical. Calculations have shown, however, that the temperature differences within a piece of cut fruit or vegetable during drying are so slight that the weakness is not important to this argument.

different rules.[16] As long as the communicating spaces are filled with liquid an actual suction will pull liquid from the larger pores to keep the finer ones saturated. When the continuity of the liquid is finally broken, the remaining evaporation takes place within the body of the moist material, and water vapor, rather than liquid water, diffuses out to the surface through the open pores. This kind of process is important in the drying of sand or wood pulp, and is undoubtedly a factor in the drying of wood. It does not appear to be significant in the drying of the common fruits and vegetables.

The statement is sometimes made by writers on the subject of dehydration that if drying conditions are made too severe internal diffusion of moisture cannot keep up with the surface evaporation. The saying contains just enough truth to be misleading, for it seems to imply that only moderate drying conditions should be used, in order to allow the internal diffusion to stay in step. This is not necessarily true. During the early stages of drying the surface does remain moist, the liquid there has essentially the same vapor pressure as pure water, and the loss of water by evaporation is substantially compensated by the shrinkage in volume of the piece. From the moment these conditions cease to hold, and until the very end of the drying process, evaporation at the surface must always be a little more rapid than the rate of supply of more moisture from the deeper layers, for that is just another way of saying that the surface layer gradually becomes drier. It is entirely appropriate, of course, to advance the following argument: Since it is conceded that the diffusivity of moisture in nearly dry tissue is very much lower than in moist tissue, would not the total drying time be shortest if somehow we could keep the surface layers as moist as possible all the time? Considerable study has been given to this question, and the answer is almost certainly no.[17] The reason, although this may not be immediately obvious, is that the proposal is self-defeating; the surface can be kept more moist only by drying at a slower rate. Another aspect of the same question will be taken up in the section of this bulletin which discusses shrinkage during drying.

The practical result of the greater and greater hindrance to moisture movement within the piece as drying progresses is that the drying rate of the common vegetables has become very low even before the moisture content falls to the desired final level of 4, 5, or 6 percent. Figure 8 illustrates this fact. It shows how the moisture content changes with time, for potato half-dice being dried on wood-slat trays under a certain set of constant drying conditions.[18] About 99 percent

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[16] O. A. Hougen, H. J. McCauley, and W. R. Marshall, Jr. Limitations of diffusion equations in drying. Trans. Amer. Inst. Chem. Engin., 36(2):183-209 (1940).

[17] See J. Crank, The influence of concentration-dependent diffusion on rate of evaporation. Proc. Phys. Soc. (London) B, 63:484-491 (1950).

[18] The curve of Figure 8 is calculated from drying rate data published by the Western Regional Research Laboratory in Bureau Circular AIC-31-VII, March 1945.

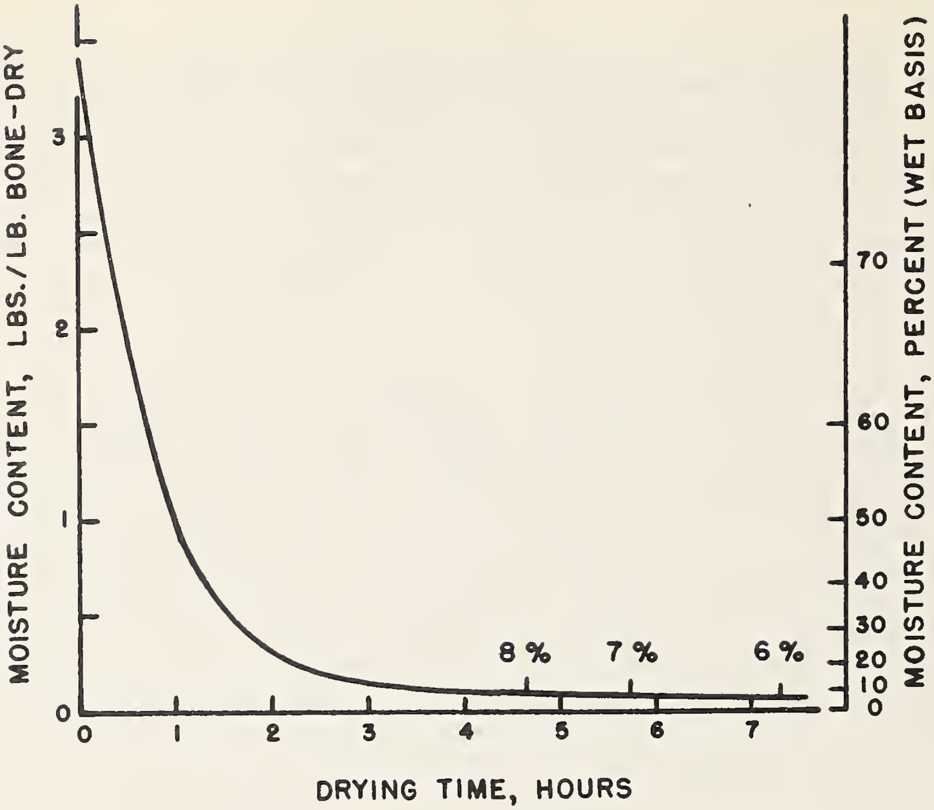

FIGURE 8–EXPERIMENTAL DRYING CURVE

of the total evaporation in this experiment has taken place in the first half of the run; the remaining half of the time is consumed in reducing the moisture content from about 10 percent down to 5 percent.

II-D. Diffusion of Sugars and Other Constituents in Solution

Water is not the only substance which changes its location within the piece as drying occurs. The water in vegetable tissues exists, as a matter of fact, as a solution of sugars, salts, and numerous other more complex constituents. The press juice from fresh carrots, for example, contains about 6 percent sugar in solution. During the drying some of these dissolved substances also migrate within the piece.

In the living vegetable tissue only the water will diffuse at all readily through the walls of the living cells. Scalding, or blanching, to which most vegetables are subjected before they are dried, changes the character of the cell walls so that they not only permit water to pass through more readily, but will also allow some of these dissolved substances to escape too.

We have already seen that when evaporation of water occurs at the surface of a piece the outermost layers of tissue become drier than those just beneath them, and that, in fact, a gradation of moisture content will soon exist throughout the piece, each succeeding layer from the center outward being a little drier than the one below it. But it is apparent that since the liquid content of the tissue cells is not pure water, but a solution, removal of part of the water from any cell leaves a more concentrated solution behind. Therefore, the gradation of moisture content within the piece must be accompanied by a gradation of the concentration of sugars and other soluble substances; the most concentrated solution will be in the surface layer, the most dilute solution in the center. This difference in concentrations constitutes a "driving force" for diffusion of the soluble substances toward the center of the piece. In the finally dried piece we should expect, therefore, to find an actual accumulation of sugar and other soluble materials in the interior and a corresponding impoverishment of the outer layers in these same substances. Since they will diffuse at an appreciable rate only if they are still in liquid solution, this migration toward the center must occur only during the early stages of dehydration.

While there has been little or no quantitative study of this phenomenon, a common experience in the dehydration of potatoes, namely the occurrence of "brown centers", is at least suggestive of such an effect. The work of many investigators has shown that the susceptibility of potatoes to browning, or "heat damage", during dehydration is strongly correlated with the amount of simple sugars such as glucose in the potato.[19] Potato stock intended for dehydration is therefore generally selected or conditioned to insure a relatively low sugar content. But now if migration of sugar toward the centers of the pieces occurs during dehydration, the centers obviously become more sensitive to "heat damage" than the outer layers. Strikingly distinct brown centers in dehydrated dice, and brown streaks down the centers of dehydrated Julienne strips, are produced under some circumstances.

Unfortunately, the combination of conditions which will cause brown centers in potato pieces cannot be adequately defined at the present time. Obviously, though, one of them must be the employment of a dehydrator temperature which is high enough to cause browning of a high-sugar potato. It is probable, according to the observations of several investigators, that the browning takes place most rapidly at a given sugar content and given temperature when the moisture content has fallen to a level of 20 to 30 percent, and occurs more slowly as the moisture content is further reduced below that critical range. Too high a dehydrator temperature at the time when the centers of the pieces are passing through this critical moisture range is therefore probably one of the causes of the difficulty. Another cause must be some combination of drying conditions during the early stages of dehydration (that is, in the high moisture range) which leads to an unusually high degree of

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[19] A full discussion of this important subject is outside of the scope of the present bulletin.

migration of sugar toward the centers. Conditions which would cause rapid evaporation would also cause a steep gradation of concentrations within the pieces, and thus provide a high driving force for the migration of sugar; but at the same time these same conditions would shorten the time during which the migration could take place. In the present state of our knowledge it is not possible to evaluate these opposing influences.[20]

II-E. Equilibrium Moisture Content

We have already seen that as drying progresses the moisture remaining in the piece becomes more firmly bound to the solid constituents and consequently exerts a lower moisture vapor pressure than pure water would at the same temperature. Figure 6 (Page 32) was an illustration of this fact.

But we have also seen that the rate at which evaporation will occur at the surface of the piece is proportional to the difference between the moisture vapor pressure at the surface and the partial pressure of water vapor in the drying air. Manifestly, if we were circulating air at a relative humidity of 10 percent (that is, air in which the partial pressure of water vapor is 10 percent of the vapor pressure of pure water) there would be a large vapor pressure difference while the material remained very wet, but when the moisture vapor pressure of the piece fell to only 10 percent of that of pure water, no pressure difference would remain and evaporation would cease. The piece would be in moisture equilibrium with the air. In order to dry a fruit or vegetable to a low final moisture content we must, therefore, expose it (at least near the end of the drying) to air which is low enough in relative humidity to leave some net vapor pressure difference even at the very end of the run.

The relation of vapor pressure to moisture content varies from one material to another, and if the desired final moisture content is unusually low a determination of the moisture vapor pressure of the exact material that is to be dried may be a necessary part of the dehydration system design.[21] The results of such measurements are sometimes known as the "equilibrium moisture content" of the material in question, for reasons that the preceding paragraph should make clear, or they may be presented as "vapor pressure isotherms" of the material--isotherms

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[20] The condition of a higher sugar content in the center than at the surface could also, of course, be produced by surface leaching during blanching or subsequent washing of the blanched pieces.

[21] An instance of this occurred during World War II when it was decided to reduce the specification moisture content of spray-dried whole egg from 5 percent to 3 percent. Careful measurements of the moisture vapor pressure of the low-moisture powder were used in the design of the final stage of the modified driers. See J. W. Greene, R. M. Conrad, A. L. Olsen, and C. E. Wagoner, Production of stable spray-dried egg powder. Chem. Eng. Progress 44(8):591-602, Aug. 1948.

because a curve showing the relation between moisture content and vapor pressure or relative humidity is always shown at some constant temperature (<u>iso</u> = equal; <u>therm</u> = heat).[22] If curves are plotted as moisture content vs. relative humidity for different temperatures the curves will nearly coincide except in the region of low moisture content. Equilibrium moisture content of dehydrated vegetables is always determined on finely ground samples, in order to reduce the time required to attain substantial equilibrium with the surrounding air. This time requirement becomes greater and greater as the equilibrium moisture level becomes lower, because of the rapid decrease in the diffusivity of moisture as the material approaches dryness. Equilibrium is approached relatively quickly if the moisture content is 20-25 percent or more.

Unfortunately, knowledge of this equilibrium moisture content has little practical application to dehydrater operation, mainly because pieces of commercial size (for example the 3/8" x 3/8" x 3/16" half-dice) approach low-moisture equilibrium so excessively slowly. Equilibrium for carrot pieces containing 4 percent moisture corresponds to surrounding air conditions of about 125° dry-bulb and 90° wet-bulb temperature, but under these conditions a very long time is required to dry carrot pieces even to 7 percent moisture, to say nothing of 4 percent.

Both in commercial dehydration and in experimental work, the drying sometimes appears not only to slow down as the low-moisture range is approached, but actually to stop, at a moisture content well above the theoretical equilibrium level. This may sometimes be due to a fluctuation in air humidity due to faulty temperature control, but for practical purposes the sharp drop in drying rate which always occurs gives almost the same impression of a complete end to the drying. The moisture level at which this occurs depends upon the kind of vegetable being dried, the previous drying conditions, the thickness of the pieces, and other factors which are discussed in later sections of this bulletin. A kind of rough general average may be struck, however, which will have some value as an indication of practical upper limits for humidity or lower limits for temperature in the finishing section of a dehydrater. Figure 9 is such a composite picture, translated into terms of dry-bulb and wet-bulb temperature instead of relative humidity.[23] A rough average of this kind can be used only because practically it is necessary to choose finishing conditions which give ample leeway. As in all physical processes, action becomes slower and slower as a condition of equilibrium is approached. An appreciable driving force must remain if the rate of final drying is not to become unreasonably slow. For example, suppose a final moisture content of 5 percent is required (that is, T = 0.053 pounds moisture per pound dry matter), and other considerations

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[22] See references in second footnote, page 32.

[23] The moisture contents given in this chart are appreciably higher than those shown in a chart published in Oregon Agri. Expt. Station Bulletin 417, Commercial dehydration of fruits and vegetables, by E. H. Wiegand, H. S. Madsen, and F. E. Price, May 1943, page 12.

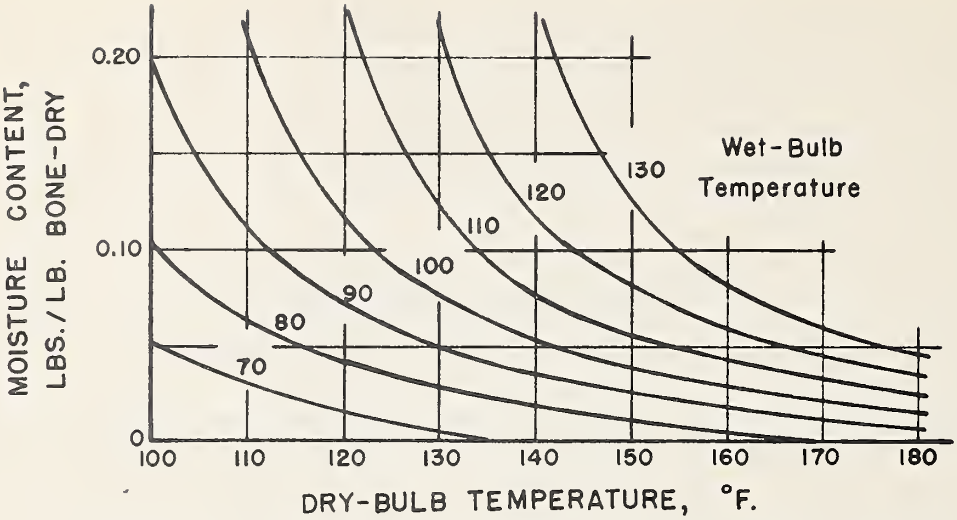

FIGURE 9—APPARENT EQUILIBRIUM MOISTURE CONTENT

limit the temperature to 160°; from Figure 9 a wet-bulb temperature of about 112° corresponds to "apparent equilibrium" at 5 percent moisture, but in order to assure a reasonable rate of final drying, the dehydrator will be operated, in practice, at a lower wet-bulb temperature than that. A full discussion of the method for determining the optimum wet-bulb temperature level is beyond the scope of this bulletin. The method comprises making quantitative estimates of the drying times for each of a number of assumed conditions, balancing the various cost factors which are involved, and also taking into account the effect on product quality. See also the discussion in section IV-F of this bulletin.

There is now an impressive amount of evidence that the stability of dehydrated foods during storage at such temperatures as 100° F. is improved if the moisture content of the products is reduced below the levels that have been customary. In view of the foregoing discussions, this more complete dehydration obviously may require special measures in the final stage of drying. Suppose, for example, that potato pieces are to be dehydrated to 2 percent moisture at a temperature of not over 140° F. A vapor pressure isotherm for potatoes at this temperature shows that the moisture vapor pressure is only 0.23 inch of mercury at 2 percent moisture; since the vapor pressure of water at 140° is 5.88 inches (Table 1), the corresponding relative humidity (equation 1) is only 4 percent. Reference to the humidity chart (Figure 3) shows that at 140° and 4 percent R.H. the absolute humidity is 0.0048 pound of water vapor per pound of dry air. Now this is a lower absolute humidity than can be counted upon to prevail in any agricultural section of the United States, and that means that normal outdoor air, heated to 140°, would not dry potatoes to 2 percent moisture even in an indefinitely long time, much less provide a margin of "driving force" which would insure reasonably rapid drying.

Several alternative procedures may be used in such a situation. One is to abandon any attempt to do the last stage of the drying in a dehydrator, and instead to include a small packet of a moisture absorbent, such as quicklime, in the final package of dehydrated product.[24] This procedure, developed by workers in the Western Regional Research Laboratory and called in-package desiccation, has been included in a Quartermaster Corps purchase specification for dehydrated vegetables. Within the package, after sealing, the pieces of product are soon surrounded by air of very low absolute humidity. A slow exchange of moisture takes place, and in the course of a few weeks at ordinary storage temperatures the moisture content of the product may be reduced to only 1 to 2 percent. Fortunately, if the package is stored at a relatively high temperature, such as would ordinarily bring about rapid deterioration, the moisture transfer is also speeded up and the product reaches the safer low moisture content more quickly.

A second kind of procedure would be to dehumidify the air furnished to the last stage of the dehydrator. If this last stage is a so-called finishing bin, only a relatively small volume of air need be supplied, and dehumidification (which means actual reduction of the absolute humidity of this air) can be accomplished in several well known ways such as are used in air-conditioning--adsorption on silica gel or activated alumina, absorption in concentrated lithium chloride solution, compression, or refrigeration.[25] Still a third way of doing the final drying would be to use a vacuum drier for the last stage. The efficacy of vacuum drying depends essentially upon the same principle as dehumidification of the drying air, namely, reducing the partial pressure of vapor in the drying chamber. When the total pressure in the space is reduced, the partial pressure of the vapor is reduced proportionally. Thus, suppose that in the example cited above, the partial pressure of water vapor in the drying air should be not more than 0.10 inch of mercury, in order to provide a sufficient difference from the 0.23-inch vapor pressure of the 2 percent potatoes at 140°. Then if the outside air has an absolute humidity of 0.015 pounds of water vapor per pound of dry air, the partial pressure of water vapor in it at a 29.92-inch barometer is 0.702 inches of mercury (equation 2). The partial pressure of vapor can be reduced to 0.10 inch by reducing the total pressure to $0.10 \times 29.92/0.702 = 4.25$ inches of mercury--that is "25.67 inches of vacuum". A final vacuum drying step has been used commercially for a number of years as a means of making very dry dehydrated fruits, such as "apple nuggets".[26]

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[24] L. B. Howard. Significance of moisture content of dehydrated vegetables. Canner, 100(3):46-48, Feb. 1945.

[25] See the comprehensive staff report entitled "Conditioning of gases and air", Chem. Met. Eng. 47(5):286-332 (1940). Also Chemical Engineers' Handbook, 3rd Ed., pp. 877-884.

[26] The principles of vacuum drying, as applied to materials like vegetables at low moisture content, have received very little study. Heat must be supplied mainly by conduction or radiation. If the total pressure in the vacuum drier is reduced below the vapor pressure of the moisture

II-F. Effects of Shrinkage During Drying

As water is lost from any of the cells of vegetable tissue during drying an internal tension is set up which pulls the cell walls inward. This process, occurring throughout the piece, is responsible for the volume shrinkage which takes place. During the early stages of drying the cells which are losing moisture deform so as to remain full of liquid; thus it comes about, as stated in a previous section of this bulletin, that the shrinkage in volume during these early stages is very nearly equal to the volume of water lost by evaporation.

When the outer layers of a piece become appreciably drier than the deeper layers they tend to shrink down onto a nearly incompressible inner core which retains nearly its original volume, and are therefore put under considerable tension. This condition becomes important in the drying of such materials as lumber. If the tension becomes greater than the strength of the outer layers, surface cracks open up, and in any case strains remain which will warp the piece. The condition is called "case-hardening".27/ In order to avoid it, lumber is dried under conditions (high wet-bulb temperature, low wet-bulb depression) which favor relatively rapid diffusion of moisture from the deeper layers and which do not cause extremely rapid drying of the outer layers. Similar effects are not known to take place in the drying of cut pieces of fruit or vegetables. That a substantial tension in the outer layers exists for a while here too is, however, shown by two kinds of experimental observation. If a cross-section of a piece of dehydrated vegetable is examined under the microscope, the outer layers of cells are found to be drastically stretched and flattened.28/ Then again, if potato dice are examined after a very short time under conditions of rapid drying they are found to have taken on the "pillow shape" of sketch b in Figure 10; not much change in volume will have occurred from the cubical shape of sketch a, but the corners will have pulled in. As drying and shrinkage become appreciable in the deeper layers of the piece the convex faces pull in and become concave, so that the piece ends by looking like sketch c, although usually somewhat twisted and otherwise distorted.

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in the piece while the latter is still somewhat soft, "boiling" of the moisture occurs, fine steam bubbles are formed, and the piece is puffed. Means of keeping the partial pressure of water vapor low in the air surrounding the product have not been fully explored; they include the controlled bleeding of fresh air into the vacuum drier and the use of special propellor-type fans to circulate the low-pressure vapor within the drier and over the heating surfaces. A further brief discussion of vacuum drying will be found in section III-I of this bulletin.

27/ The term has been somewhat loosely used in the vegetable dehydration industry to describe the condition of dry surfaces and moist centers in the pieces. As has been said above, this is a normal consequence of rapid drying, and a word like "case-hardening", which commonly connotes trouble, is not appropriate.

28/ R. M. Reeve. Facts of vegetable dehydration revealed by microscope. Food Indus. 14(12):51-54 (1942).

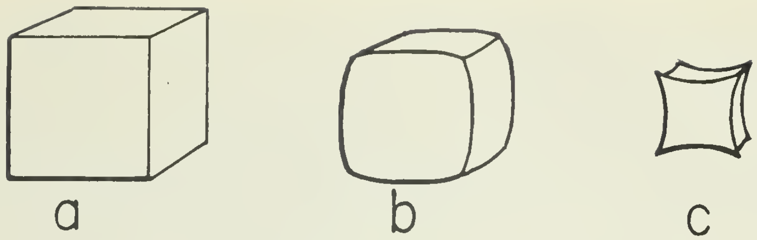

FIGURE 10 – CHANGE IN SHAPE OF DICE DURING DRYING

If the drying conditions during the entire time that any portion of the piece remains moist and plastic are so gentle that the surfaces are never much drier than the center, the piece will shrink down with a minimum of distortion. On the other hand, under very rapid initial drying conditions the outer layers will become dry enough to be quite rigid and have considerable mechanical strength while the inside must still undergo further shrinkage and is still relatively moist and weak. Under these circumstances the final volume of the piece is substantially "set" while the average moisture content of the piece is quite high; the internal tissue splits in one or several places, and shrinks outwardly toward the "set" outer faces. If the finally dry piece is cut open it will be found to contain voids, or a hollow center. The contrast between the volumes occupied by slowly dried and rapidly dried potato dice is pictured in Figure 11, which shows two beakers containing equal weights of the two products.[29]

This fact has obvious significance with respect to the "space saving" aspect of food dehydration. If it is essential to pack as much food as possible into a Number 10 can, then slow dehydration is a way to accomplish that result. However, there are always other considerations besides space saving. One of them is ease of reconstitution and preparation of the food for serving, and there is a limited amount of evidence that as the density of the product increases reconstitution becomes slower and more difficult. Another point is that bacterial and mold growth or actual spoilage may become serious during very slow drying at moderate temperatures, as well as adverse changes in color, flavor, and vitamin C content. In addition, as will be more fully discussed in a later section of this bulletin, a fully shrunken, very dense piece loses moisture more slowly

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[29] These experiments, conducted by P. W. Kilpatrick in the Western Regional Research Laboratory, were run under the following conditions: 3/8-inch potato dice, 3-minute steam blanch, loaded on metal-grid trays at 1/2 pound per square foot. Air velocity 800 feet per minute. Fast drying, 150°, wet-bulb 85°, 3-3/4 hours to $T = 0.11$. Slow drying, 125°, wet-bulb 120°, 10-1/2 hours to $T = 0.61$, then 150°, wet-bulb 85°, 4-1/2 hours to $T = 0.11$, total time 15 hours.

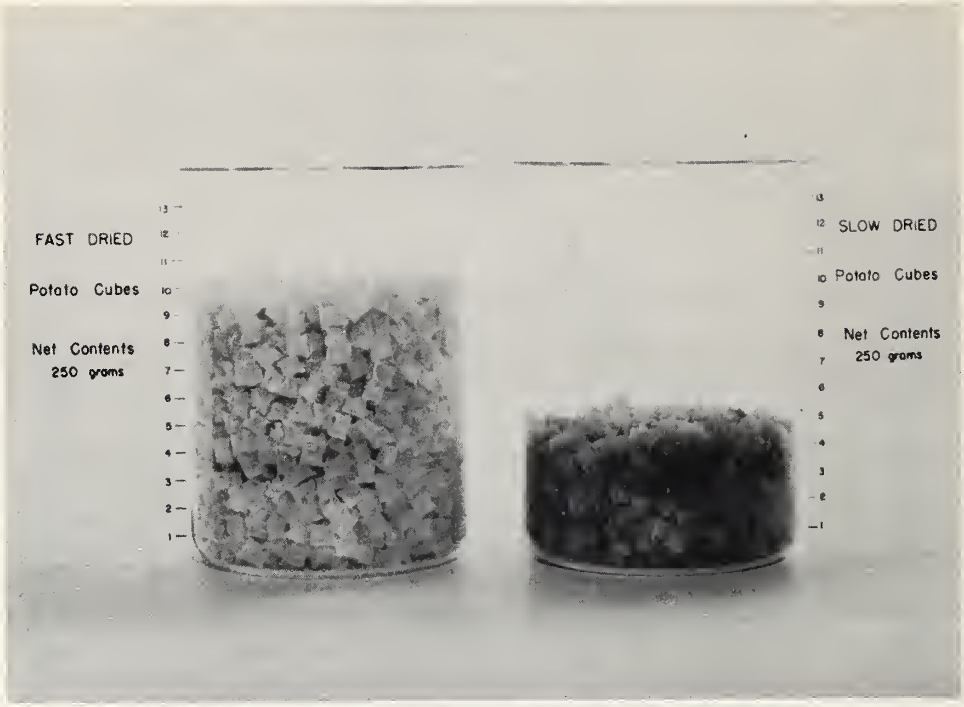

FIGURE II – RELATIVE BULK OF RAPIDLY DRIED AND SLOWLY DRIED POTATO DICE

in the final stages of dehydration to low moisture content than a piece which has retained a larger external size and has become somewhat porous internally. It is as though a dehydration run which starts rapidly can also finish rapidly, while one which starts slowly must perforce also finish slowly. Thus, while the dehydrator operator can exert some control over the density of the final product, he should weigh several considerations before he makes his choice.

III. DRYING RATES, AND THEIR DETERMINATION AND PREDICTION

> This chapter describes the method used for the experimental determination of drying rates, and then discusses in detail the effect upon drying rate of changing the wet-bulb depression, the dry-bulb temperature, the air velocity, the load of product per unit area of support, the type of drying tray, the kind of material being dried, the shape and size of the pieces, and the barometric pressure.

The foregoing sections of this bulletin have discussed the factors which influence the hot-air drying of vegetables, but both the designers and the operators of dehydrators need specific information about the rates at which different vegetables will dry under the range of conditions likely to be encountered in commercial dehydrators. The designer must have an estimate of drying time in order to determine the dimensions, the air flow, and the heat supply required for a drier of a given capacity. The operator needs a rational basis for the determination of best tray-loading density and the proper degree of recirculation of air, both of which are inseparably related to drying time. If an existing dehydrator is to be used for some new product, an estimate of the drying time of the new product at the given air flow and heating capacity must be made before accessory preparation and packaging equipment can be properly designed to match in capacity.

The technology with which we are mainly concerned in this bulletin is that of drying cut pieces of vegetable in a current of air. Other methods of drying, such as spray drying, air-suspension drying, drum drying, vacuum drying, and infra-red drying, are important for certain products, but as concerns vegetable dehydration they are either still under research investigation or have rather limited usefulness; at any rate, there is little published information about the rates of drying in these processes or about the factors which influence the rate. In contrast, we know a great deal about the drying rates of the commonly dehydrated vegetables in hot air "tunnel driers".

The time required to dry prepared pieces of a vegetable in a hot-air dehydrator is known to depend upon at least the following factors: variety of vegetable (as reflected in the physical properties and chemical composition of the pieces to be dried), method of preparation (for example, the degree of blanching), shape and size of piece, thickness of layer of pieces on the support, type of support, mode of exposure to the air stream, the temperature, humidity, and velocity of the air stream, the barometric pressure, and such changes in the foregoing factors as may occur in the course of the drying because of the type of drying schedule which is used. That is, the drying time depends upon both the characteristics of the dehydrator and the properties of the wet material itself.

III-A. Determination of Drying Rates

The older literature on dehydration of fruits and vegetables usually lists the normal, or expected, drying time for each kind of product, along with a maximum recommended air temperature, but little or nothing else to specify the other factors which are known to affect drying rate markedly. More recently a number of different investigators have made more or less elaborate measurements in which at least some of the various factors were separately evaluated.1/ A. H. Brown, P. W. Kilpatrick, M. E. Lazar, and their coworkers at the Western Regional Research Laboratory have made the most comprehensive investigations of the drying rates of the common vegetables.2/ Most of the following discussion is based upon the latter studies.

The number of independently variable factors is so large that it is manifestly impossible to study separately all of their possible combinations. The following experimental method has therefore been used: In each of a series of drying runs made in a carefully designed laboratory drier, all of the conditions are kept as nearly as possible constant from the beginning to the end of the run, and the loss of moisture is determined frequently by weighing the experimental tray load. One run in the series is picked to be the "reference run", with values of all

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1/ See especially: C. W. Culpepper and H. H. Moon. Factors affecting the rate of drying of Kieffer pears. USDA Tech. Bull. 592. Dec. 1937.
Rene Guillou. Developments in fruit dehydrator design. Agric. Engin. 23(10):313-316. Oct. 1942.
W. R. Marshall, Jr. The drying of foods. Heating, Piping, and Air Condg., 14(12):724-728. Dec. 1942.
W. V. Cruess and G. Mackinney. The dehydration of vegetables. Univ. of Calif., Agr. Expt. Station Bull. 680, Sept. 1943, pp. 15-19, 41-43.
R. L. Perry. Heat and vapor transfer in the dehydration of prunes. Trans. Am. Soc. Mechan. Engin. 66:447-456 (1944).
R. L. Perry, E. M. Mrak, H. J. Phaff, G. L. Marsh, and C. D. Fisher. Fruit dehydration. Univ. of Calif., Agr. Expt. Station, Bulletin 698, Dec. 1946, pp. 44-47.
A. J. Ede and K. C. Hales. The physics of drying in heated air, with particular reference to fruits and vegetables. Dept. Sci. and Indus. Research (Great Britain), Food Investig., Special Report No. 53 (1948).

2/ A. H. Brown and P. W. Kilpatrick. Drying characteristics of vegetables--riced potatoes. Trans. Amer. Soc. Mech. Engin. 65(11):837-842 (1943).
The application of drying-rate nomographs to the estimation of tunnel dehydrator drying capacity. Bureau Circular AIC-31, Western Regional Research Laboratory, U. S. Department of Agriculture, Albany, California.
I. Riced white potatoes (Rev. June 1947)
II. Sweet corn (Nov. 1943)
III. White potato strips, through-flow conditions (Jan. 1944)
IV. Shredded cabbage (Feb. 1944)
V. Onion slices (April 1944)
VI. Sweetpotato strips (Sept. 1944)
VII. White potato half cubes (March 1945)
VIII. Carrot pieces (May 1947)

the variable factors approximately midway between high and low extremes. The two or more other runs in the series each are also conducted under constant drying conditions, but some one of the variable factors is given a lower value than the "reference" in one of them, a higher value than the "reference" in another. Then another series is run; a different variable factor is given at least one lower value and at least one higher value than the "reference". Still a third factor is varied in a third series, and so on. Finally, certain special runs are made, with two or more of the factors differing from the "reference" at the same time.[3] Each one of this long program of drying experiments results finally in a "drying curve", moisture content plotted against time, of the kind illustrated in Figure 8 (page 36).

Now in a commercial dehydrator the pieces of fruit or vegetable are never subjected to constant drying conditions, because such a process would be unduly wasteful and expensive--instead, the temperature, the humidity, and sometimes the air velocity and certain other factors, change in a predictable way as the pieces become drier. That is, by making use of our knowledge of the properties of air, water vapor, and heat, we shall be able to say that at the point in a certain dehydrator where a particular product has dried down to a moisture content of, say, 1.53 pounds of moisture per pound of dry solids, the temperature will be 146° F. and the wet-bulb temperature 95° F. Here we make a connection with the constant-condition drying experiments, for perhaps we can assume that the <u>rate</u> of drying at that point is the same as it would be at a moisture content of 1.53 in a drying experiment run under unvarying conditions of 146° and 95°. We know, in fact, that this assumption cannot be quite true, and the qualification will be noted more fully below; but in general, it turns out that if we make the assumption, and piece together the rates that would prevail from section to section of the real dehydrator, we get a good estimate of the actual drying time.

In order to make this process of drying time estimation as convenient as possible, Brown and his associates at the Western Regional Research Laboratory have correlated the results of their experimental drying runs in nomographs (that is, alinement charts which are read by use of a straightedge) which are published in the AIC-31 series of Bureau Circulars referred to in a footnote above. These charts cannot be satisfactorily reproduced in this bulletin; the Circulars can be obtained by request addressed to the Western Regional Research Laboratory. They have been used to derive most of the examples given in later sections of this bulletin to illustrate the effects of various factors upon drying time.

We said in a preceding paragraph that the rate of drying at a given moisture content, temperature, and humidity cannot be quite the same in a constant-condition drying experiment as in a dehydrator where the

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[3] Those who are familiar with the design of factorial experiments will recognize the necessity for such special runs, because the effects of the different factors cannot be expected to combine linearly.

temperature and humidity change as drying progresses. The reason is, of course, that the rate of loss of moisture during the early stages of drying affects both the internal distribution of the remaining moisture and the manner in which volume shrinkage takes place, and these differences in turn will affect the rate of drying in later stages. Fortunately, however, from the standpoint of simplicity of application of the data, the effect upon drying rate appears to be minor except in the low-moisture range--that is, below a moisture content of 10 to 20 percent. The effect has been carefully studied by the Western Regional Research Laboratory workers for only one product, riced white potatoes (AIC-31-I); its quantitative evaluation for potato dice and for the other vegetables will require further research. The following example will give an idea of its magnitude: Riced white potatoes are dried to a moisture content of 0.10 pounds of moisture per pound of dry solids under one set of dehydrator conditions in an elapsed time of 3.5 hours, and under a different set of dehydrator conditions in an elapsed time of 1.75 hours; the final stage of drying down to a moisture content of 0.06 pounds of moisture per pound of dry solids is conducted in both cases at a temperature of 140° and a wet-bulb temperature of 90°. Then the AIC-31-I nomographs predict that this final stage will require 1.16 hours of further drying in the first case, and only 0.71 hours in the second case.[4]

In the following paragraphs all of the examples are based upon laboratory experiments in which the drying conditions were kept constant during an entire run, in order to show clearly the separate effects of the different factors which influence the drying rate. Examples of the more complicated effects which occur in commercial dehydrators will be taken up later in this bulletin.

III-B. Effect of Changing the Wet-Bulb Depression at Constant Temperature

As would be expected, a large wet-bulb depression (difference between dry-bulb and wet-bulb temperatures) is favorable to rapid drying. Figure 12 illustrates the effect by showing four drying curves for potato half-dice (3/8 x 3/8 x 3/16 inch, in the wet state), dried on metal-grid trays loaded with 1.5 pounds of the prepared dice per square foot, and exposed to an air stream with a velocity of 800 feet per minute, and a temperature of 160°. The wet-bulb temperatures in the four runs shown were 90°, 100°, 110°, and 120°, corresponding to wet-bulb depressions of 70°, 60°, 50°, and 40° respectively. Moisture contents in Figure 12 (as in all of the similar illustrations in this section) are expressed as the ratio, pounds of water per pound of dry solids, and are plotted on a logarithmic scale in order to emphasize the low-moisture end of the curves.

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[4] An appreciable effect of the same kind was noted in experiments on the drying rate of carrot half-dice, but it was less marked than in the case of riced potatoes and was not given a quantitative expression in the nomographs for carrot half-dice, AIC-31-VIII.

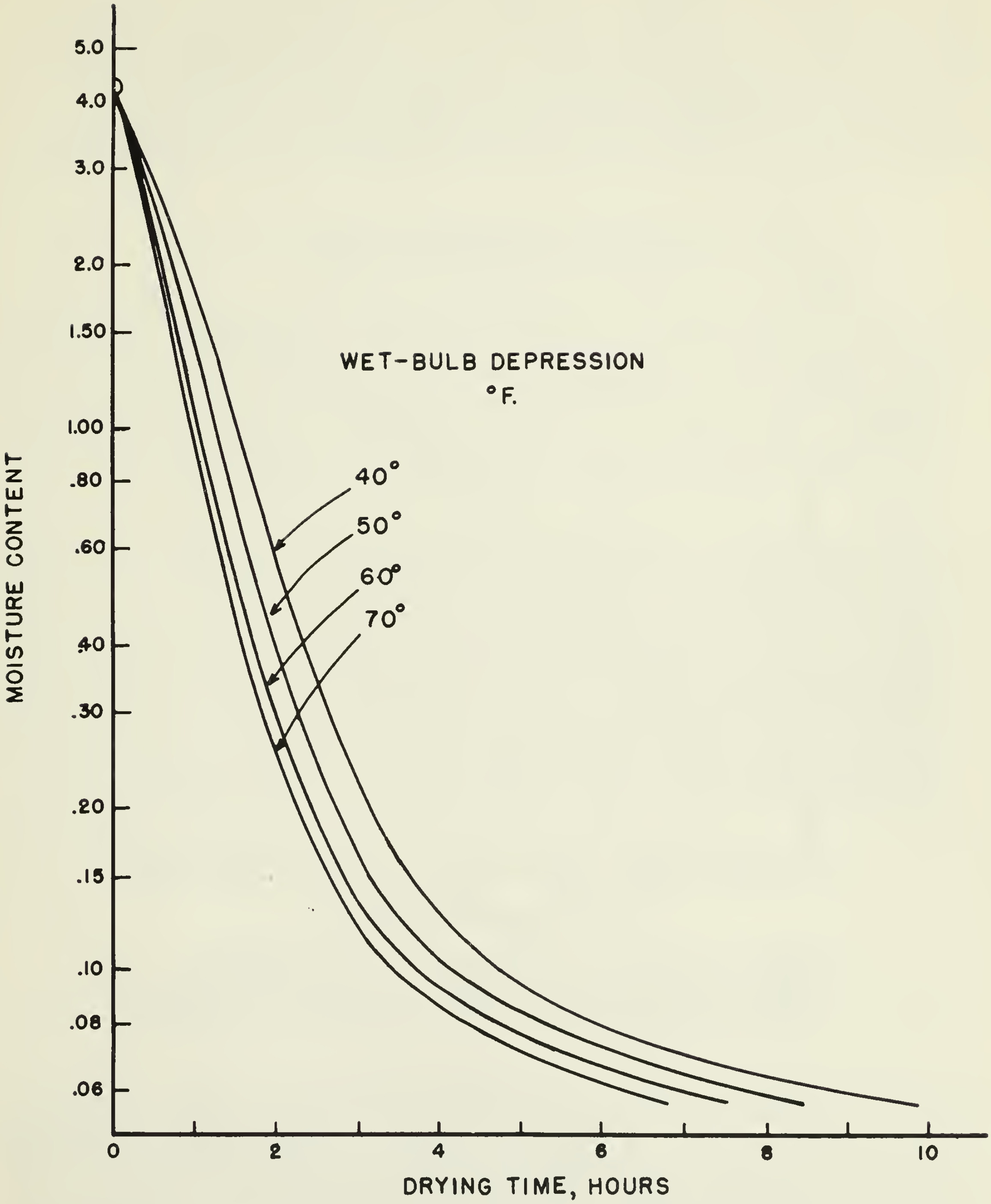

FIGURE 12-EFFECT OF WET-BULB DEPRESSION ON DRYING TIME

While the increase in rate of drying is evidently substantial, it is not quite proportional to the increase in wet-bulb depression, as will be seen from Figure 13. In this illustration the average rate of loss of moisture (dry basis) per hour in the four runs shown in Figure 12 is plotted against wet-bulb depression. Quite similar curves are obtained if instead of the average drying rate for the whole run, down to a moisture content of 0.06, the average drying rates for only the high-moisture portions of the curves are plotted against wet-bulb depression.

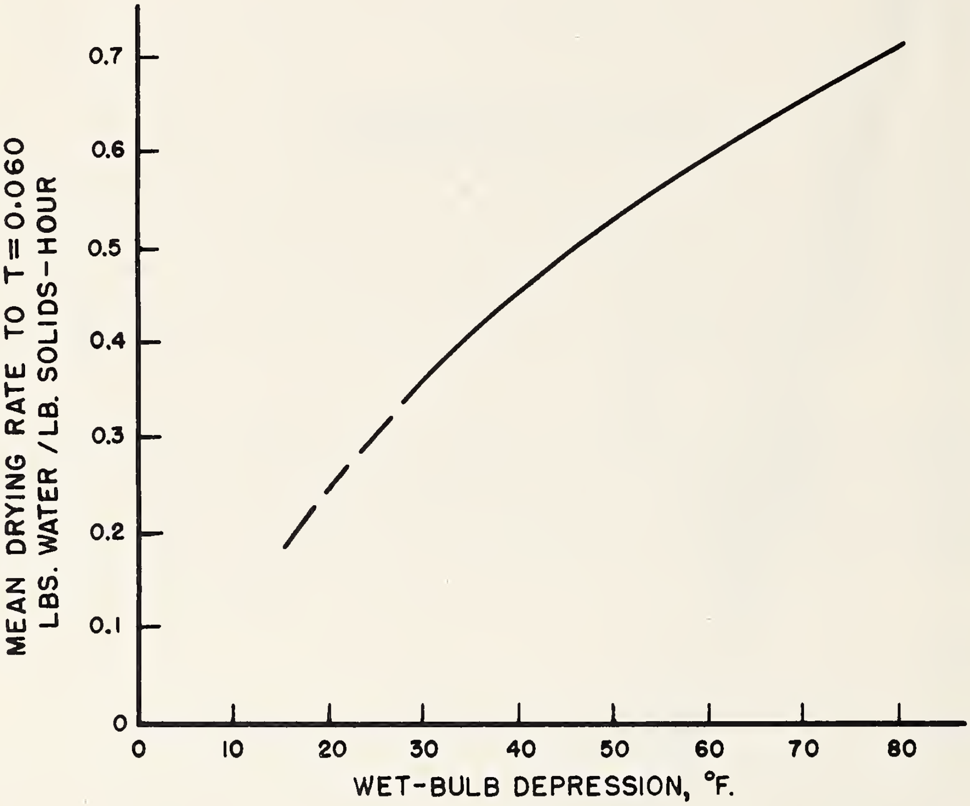

FIGURE 13-EFFECT OF WET-BULB DEPRESSION ON MEAN DRYING RATE FROM T=4.3 TO T=0.06

The British investigators Ede and Hales[5] found that the drying rates of potato and carrot strips and shredded cabbage are approximately proportional to wet-bulb depression at the higher levels of moisture content, although considerable divergence from proportionality was apparent in some of their experiments at moisture contents as high as 2.0. In contrast to this behavior of cut vegetables, Perry, Guillou, and their co-workers at the University of California[5] showed that the drying rate of prunes

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[5] See first footnote, page 46.

above a moisture content of about 0.20 is substantially independent of wet-bulb depression so long as the relative humidity of the air is less than about 40 percent. Both Ede and Hales and Brown and his associates found that drying rates of the common vegetables below a moisture content of 0.10 to 0.20 are little affected by wet-bulb depression so long as the moisture content is well above the equilibrium value.

III-C. Effect of Changing the Temperature, at Constant Wet-Bulb Depression

Figure 14 shows the effect of changing the air temperature, but maintaining the same wet-bulb depression by changing the wet-bulb temperature by an equal amount. As in the preceding example, potato half-dice are being dried on metal-grid trays, loaded with 1.5 pounds per square foot and exposed to an air stream with a velocity of 800 feet per minute. The wet-bulb depression is 50° in all four of the runs, and dry-bulb temperatures are successively 140°, 150°, 160°, and 170°.

A rise in air temperature evidently also increases the rate of drying. There is a significant difference from the effect of wet-bulb depression, however, in that the initial rate of drying at high moisture content is substantially identical in all four of these runs, and the difference in rates only begins to appear at lower moisture levels. Since the internal temperature of the pieces of potato must be approximately 20° higher during an entire run conducted at 170° and a wet-bulb temperature of 120° than in a run at 150° and 100° wet-bulb temperature, it seems probable that the main effect of the higher temperature must be to increase the rate of internal diffusion of moisture. It will be remembered that diffusion rate is the controlling factor only during the low-moisture end of the run.

III-D. Effect of Changing the Air Velocity

Figure 15 shows four drying curves illustrating runs in which the air velocity was the only factor varied. Potato half-dice are being dried on a metal-grid tray, loaded with 1.5 pounds per square foot, and exposed to an air stream whose temperature is 160° and wet-bulb temperature 100°. Air velocities across the tray surface of 400, 600, 800, and 1000 feet per minute are maintained in the four runs. It will be seen that the curves at 800 and 1000 feet per minute velocities are practically indistinguishable, and only the 400-foot velocity is significantly different from the others. The drying rate experiments upon which these curves are based showed, however, that a change in air velocity exerts a much more pronounced effect if the trays are heavily loaded than if they are lightly loaded;[6] apparently if a thick layer

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[6] 1.5 pounds per square foot is a relatively light load.

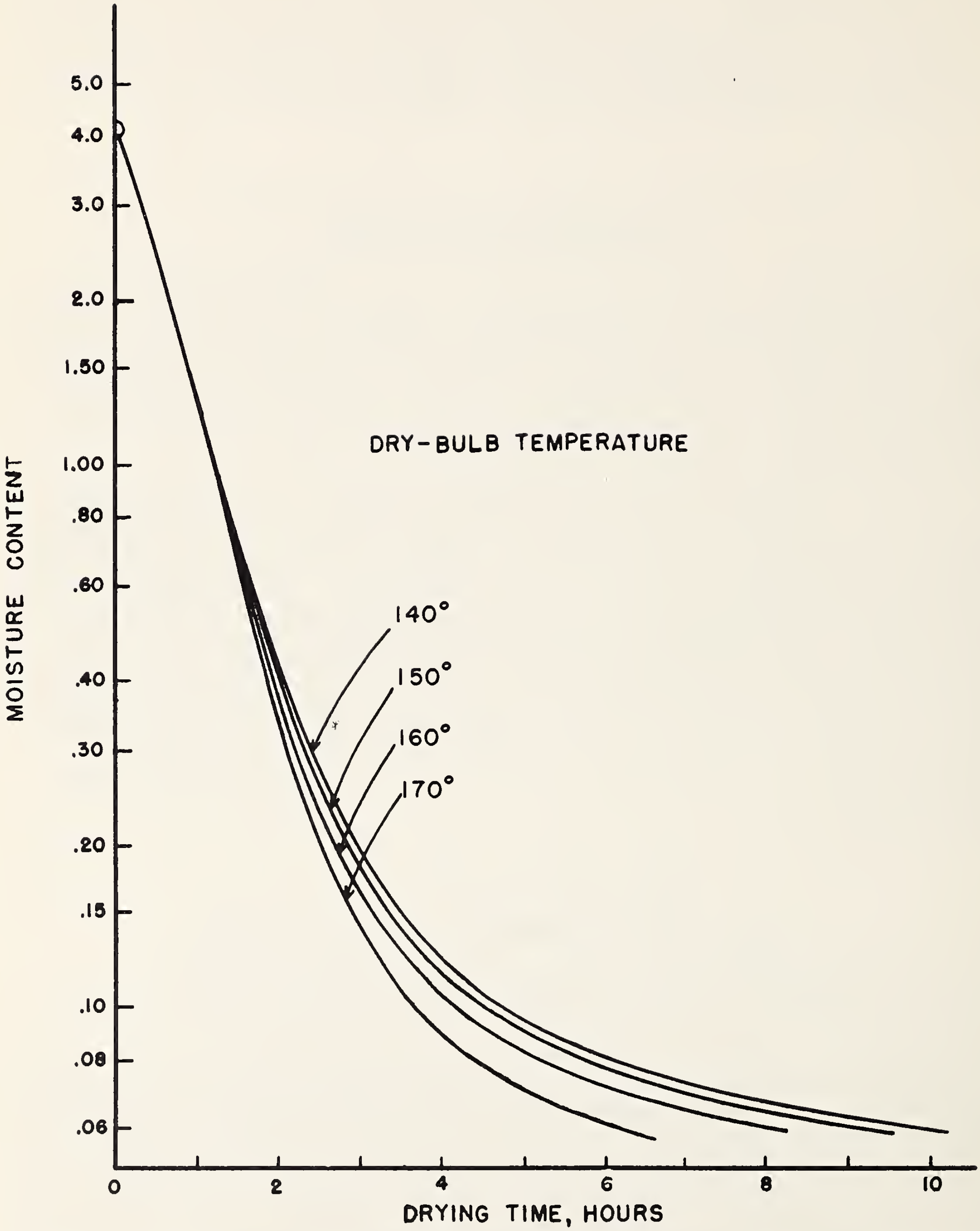

FIGURE 14 - EFFECT OF DRY-BULB TEMPERATURE ON DRYING TIME

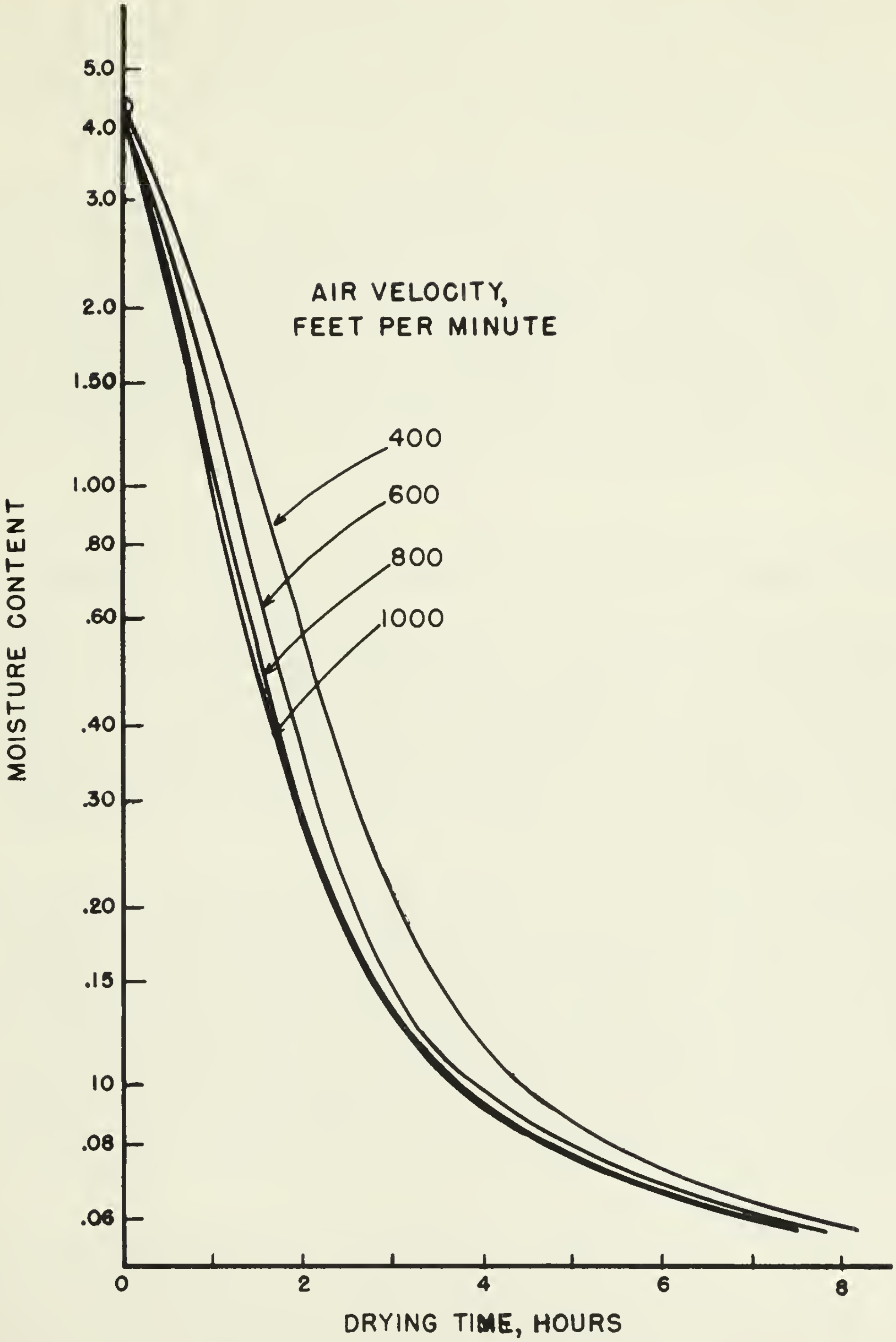

FIGURE 15-EFFECT OF AIR VELOCITY ON DRYING TIME

of vegetable pieces is piled on a tray additional air velocity across the surface brings about more turbulence of the air stream and therefore more circulation of air through the interstices of the thick layer. Some of the drying-rate nomographs of the AIC-31 series recognize this interdependence of the effects of tray loading and of air velocity by combining the two effects into a single factor.

A change in the air velocity in a dehydrator causes two quite independent effects upon its performance. One is the effect on drying rate, which has just been described. The other will be considered more fully in a following section of this bulletin, and, in brief, is a consequence of the fact that the weight of air moved through the dehydrator rises in proportion to the velocity of that air. The greater the weight of air circulated, the less it will fall in temperature for a given amount of evaporation, and hence, the greater the wet-bulb depression that will be maintained in the dehydrator.

III-E. Effect of Changing the Load per Unit Area of Support

Vegetables in piece form are almost invariably carried through the drying process either spread as a layer roughly one-half to one inch deep on shallow trays with perforated bottoms, or spread as a layer several inches deep on a slowly moving perforated conveyor. In the former, which is the common truck-and-tray tunnel dehydrator, the drying air passes mainly across the surface of the trays; in the latter the air circulation is almost always through the layer of wet material and through the conveyor perforations.

No quantitative discussion of drying rates of vegetables in the conveyor type of dehydrator is publicly available,[7] although one of the AIC-31 bulletins (No. III) contains basic information on the through-flow drying of white potato Julienne strips. Ede and Hales' bulletin[8] also contains results of drying-rate experiments on potato strips and carrot strips under through-flow exposure to the air. On the other hand, a good deal is known about the effect of the weight of product spread on a square foot of tray surface in the truck-and-tray type of dehydrator. The following discussion concerns only the latter type, that is, cross-flow drying.

Figure 16 illustrates the effect of varying the weight of potato half-dice spread on a metal-grid tray upon the mean drying rate of the entire tray-load, using 1.0, 1.5, 2.0, and 3.0 pounds per square foot of tray

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[7] See, however, W. R. Marshall, Jr. and O. A. Hougen, Drying of Solids by through circulation. Trans. Amer. Inst. Chem. Engin., 38(1):91 (1942), and W. R. Marshall, Jr., The drying of foods. Heating, Piping, and Air Condg., 14(12):724-728, Dec. 1942. Also Chemical Engineers' Handbook, 3rd Ed., pp. 826-828.

[8] See first footnote, page 46.

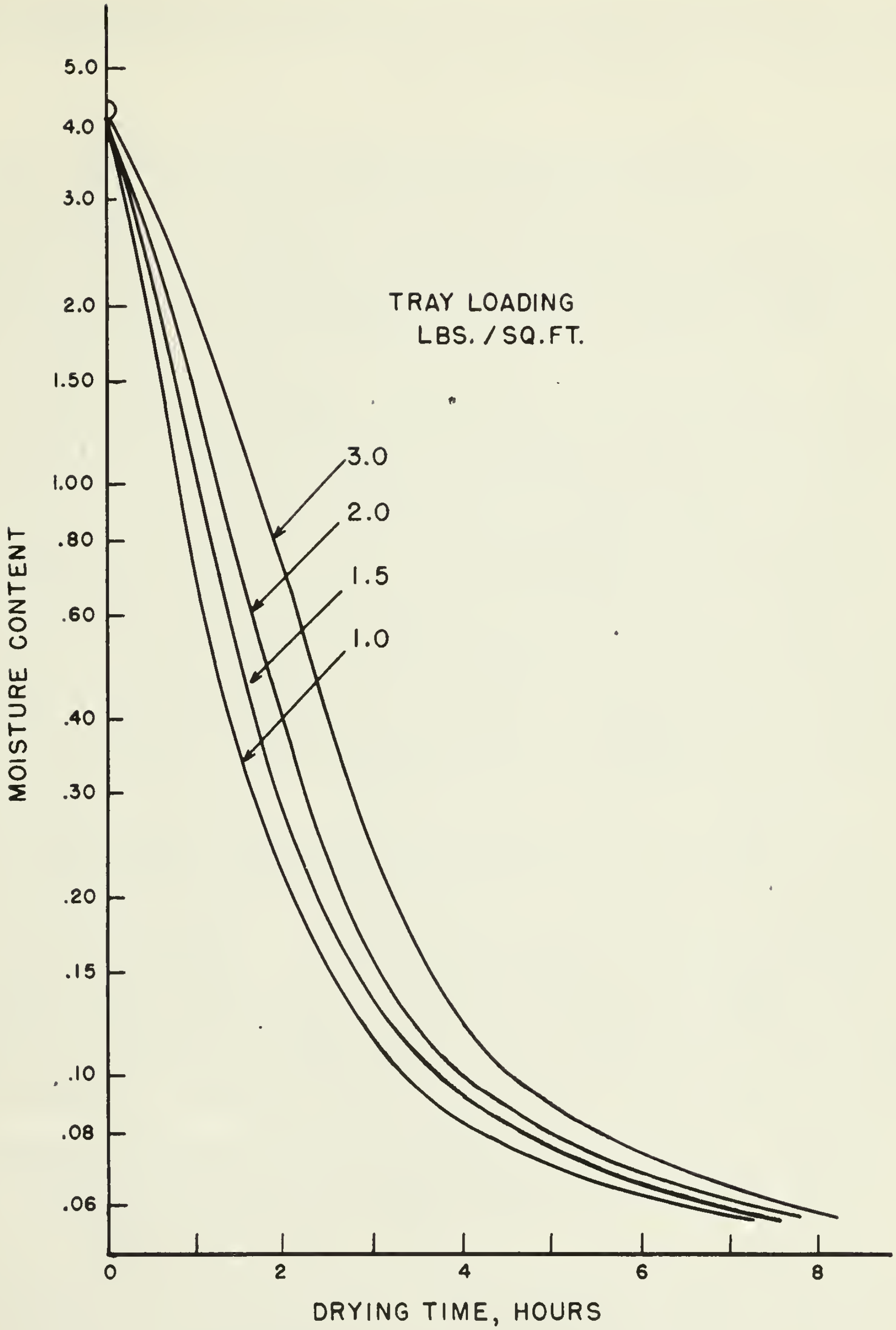

FIGURE 16—EFFECT OF TRAY LOADING ON DRYING TIME

surface; the material is exposed to constant drying conditions of 160° dry-bulb temperature, 100° wet-bulb temperature, and an air velocity across the trays of 800 feet per minute.

Increasing the tray-loading evidently reduces the rate of drying materially during the early part of the run,[9] but as the run progresses the rates become more and more nearly equal, so that at the final moisture content of 0.06 (dry basis) there is only 17 percent difference in drying times between the two extreme loadings which differ in a ratio of 3 to 1. The potato half-dice drying experiments on which the AIC-31-VII nomographs are based showed, in fact, that after the moisture content falls to about 0.20 (note that the additional drying time beyond that point may require two-thirds of the total time) no further appreciable effect of the initial tray loading can be found. Presumably the main reason for this is that in this low moisture range the rate of internal diffusion controls the rate of drying; besides, shrinkage of the pieces reduces even a 3-pound layer to a very open structure, so that the drying air can circulate nearly as freely around the pieces as about those remaining from a 1-pound layer. If the original loading were much heavier than 3 pounds per square foot this condition would probably no longer prevail, and an effect on drying rate would be found even at the low moisture levels. This is especially likely to occur if the vegetable is sliced instead of diced, for the flat surfaces of the slices will stick together, making, in effect, a much thicker piece of material through which the moisture must diffuse. A similar effect will occur if the material is so soft that the load crushes the bottom layers.

Even though a change in tray loading may have only a minor effect on total drying time under constant drying conditions, tray loading, like air velocity, influences the dehydrator performance in at least two independent ways. Besides the direct lowering of drying rate at high tray loadings, there is a greater drop in the air temperature as it passes through the drier. Both effects lead to a lengthening of the drying time. Now the daily capacity of a dehydrator, if drying time is constant, is directly proportional to the weight of material spread on the available drying surface; but if the drying time lengthens, the increase in capacity is less than proportional to the increase in loading. For a

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9/ M. E. Lazar, of the Western Regional Research Laboratory, showed in an unpublished report dated June 9, 1945, that the initial rate of drying of a trayload of 3/8" x 3/8" x 3/16" carrot half-dice corresponds approximately with the rate of evaporation from 3 to 4 square feet of free water surface per square foot of tray surface (see the discussion of this effect in Section II-B, above). The evaporation takes place almost entirely from the top layer of dice (unless the conditions are such as to cause substantial circulation of air through the layer of wet material), so that the initial rate of loss of weight from a heavily loaded tray is little, if any, greater than from a lightly loaded tray. The initial drying rate determined by weighing the whole trayload therefore is approximately inversely proportional to the initial load per square foot, down to the point at which the tray is barely covered with a single layer of pieces.

given dehydrator system it will be found that some particular tray loading gives the maximum daily capacity, any further increase in loading being more than offset by the increase in drying time.

III-F. Effect of the Type of Drying Tray

Figure 17 illustrates the effect of drying potato half-dice on two different types of drying tray--one with an expanded metal bottom, the other with a wood-slat bottom. Drying conditions are otherwise identical--dry-bulb temperature 160°, wet-bulb temperature 100°, tray loading 1.5 pounds per square foot, air velocity 800 feet per minute.

The metal-grid tray dries the potatoes faster than the wood-slat tray, and the probable reasons suggest that the exact details of tray design are important. In the first place, the expanded metal of the metal-grid tray had a much larger proportion and better arrangement of free openings than the wood-slat tray, and the surface it exposed to the air circulating beneath it probably caused more air turbulence, both of these factors contributing to a heightened degree of flow of the air through the layer of material on the tray. In the second place, as a result of the greater heat conductivity of metal, the wet material in the metal-bottom tray probably warmed up above the wet-bulb temperature of the air during the early part of the run, and this would cause an increased rate of evaporation. Finally, the wood slats absorb moisture from the wet product loaded onto them, and hold on to this moisture quite tenaciously during the later phases of the run; since the drying rate is determined by weighing the whole trayload at intervals, the potatoes will appear to be drying more slowly than they really are.[10]

Reference was made above to the advantage of inducing a considerable amount of flow of the air through the layer of wet material, even though the main air flow is parallel to the tray surface. An expedient that can be used effectively in an experimental dehydrator that holds only one or a few trays is to slant the trays so that the main air stream is impelled, at least in part, to pass through the wet layer. It has not been demonstrated that the same principle can be usefully employed in a commercial dehydrator. Another expedient that has been described[11] comprises shaping the slats of wooden tray bottoms so that they tend to scoop air from the air stream passing below the tray, and direct it up through the layer of product.

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[10] Some doubt is cast on this last inference by the fact that Brown and his coworkers were unable to find any difference in the drying rates of carrot pieces on wood slat and metal grid trays below a moisture content of 0.20.

[11] C. C. Eidt, Principles and methods involved in dehydration of apples. Canada Dept. of Agriculture, Tech. Bulletin 18 (1938).

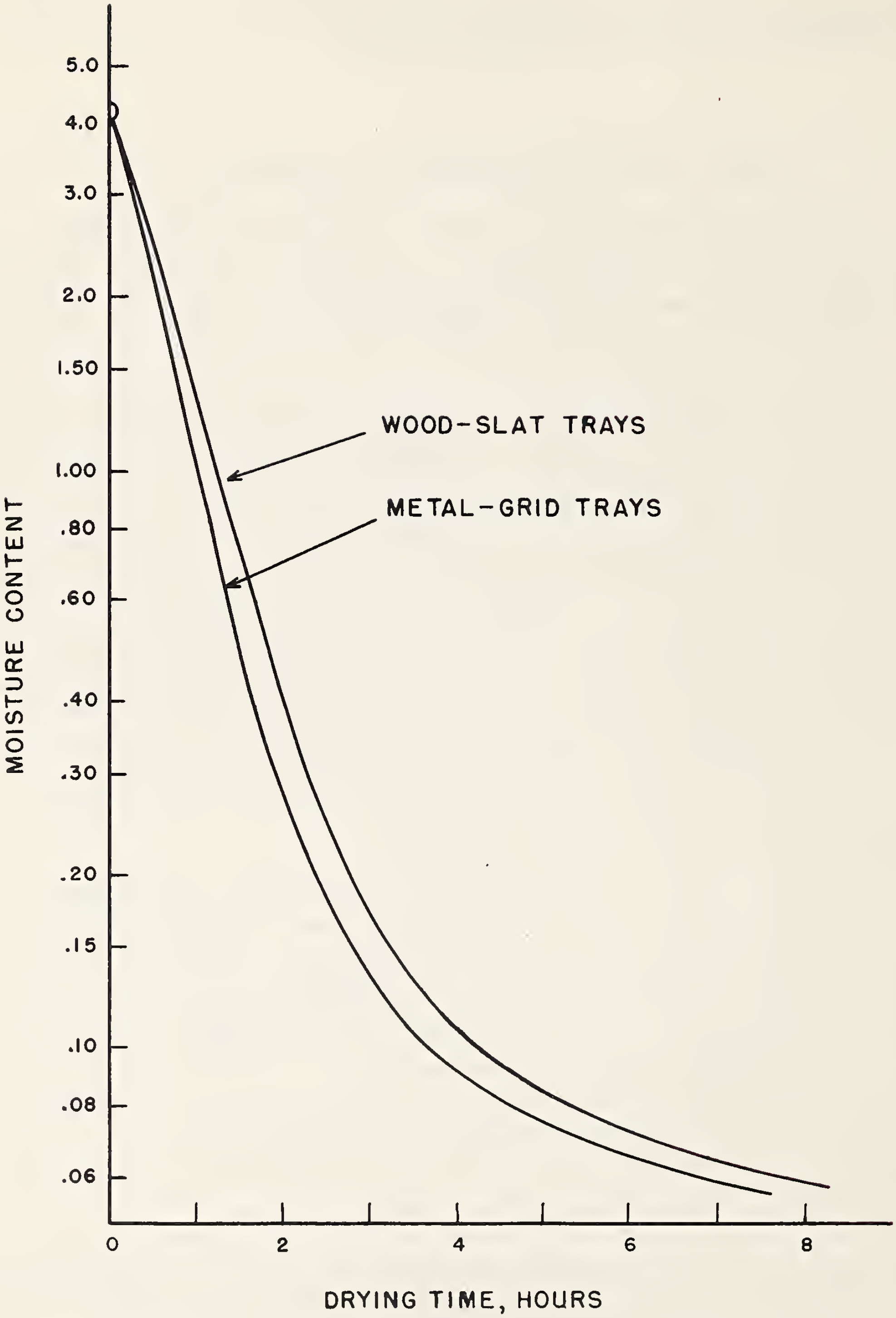

FIGURE 17—EFFECT OF TRAY CONSTRUCTION ON DRYING TIME

III-G. Effect of the Nature of the Product

No very satisfactory comparison of the drying rates of different fruits and vegetables can be made, partly because of the different forms in which they are usually prepared (dice, strips, shreds, slices, rings, eighths, halves, etc.), and partly because of their very different initial moisture contents. With regard to the latter, if carrot dice and potato dice of exactly the same initial size are compared, there is only about half as much solid matter in a carrot piece as in a potato piece; as the drying nears completion the potato pieces will be much thicker than the carrot pieces and the diffusion of moisture to the surface would be slower for that reason alone, if the composition and other properties were otherwise identical.

Figure 18 shows such a comparison between potato and carrot pieces. The pieces were not exactly the same in size, the carrot pieces being 1/4-inch thick, the potatoes 3/16-inch; both were 3/8-inch square. These sizes are nominal. The pieces were prepared by a standard commercial dicer, and a certain amount of "chaff" (that is, pieces smaller than the nominal cut) was always present--to a considerably greater extent in the carrot samples than in the potato samples. The total surface exposed per pound of wet material is therefore somewhat uncertain. Drying conditions were identical--metal grid trays, dry-bulb temperature 160°, wet-bulb temperature 100°, tray loading 1.5 pounds per square foot, air velocity 800 feet per minute. The carrot pieces reached a final moisture content of 0.06 in 5 hours, as against 7 hours for the potato pieces.

The higher initial drying rate of tho carrot pieces is probably no more than a direct reflection of the higher moisture content. If a carrot piece and a potato piece had the same surface area, the weight of moisture lost per hour during the initial phase would be substantially the same from each; but the weight of moisture lost per hour per pound of dry solids would be almost twice as high from the carrot piece as from the potato piece.

The higher drying rate of the carrot pieces in the low-moisture range may be partly due to the smaller size of the nearly dry pieces, as suggested above, and partly due to the great difference in structure and composition of these two vegetables. Our present knowledge is too fragmentary to enable us to evaluate these effects. That the matter is not simple is demonstrated by unpublished work at the Western Regional Research Laboratory on the rate of loss of moisture by products packed in closed cans containing a packet of quicklime (see the discussion of in-package desiccation, page 41). The investigators found that potato half-dice lost moisture to the lime more rapidly than carrot pieces which were originally only 1/16-inch thick, even at a storage temperature of 120°. A difference in the freedom of air circulation between pieces in the can may have had something to do with this result.

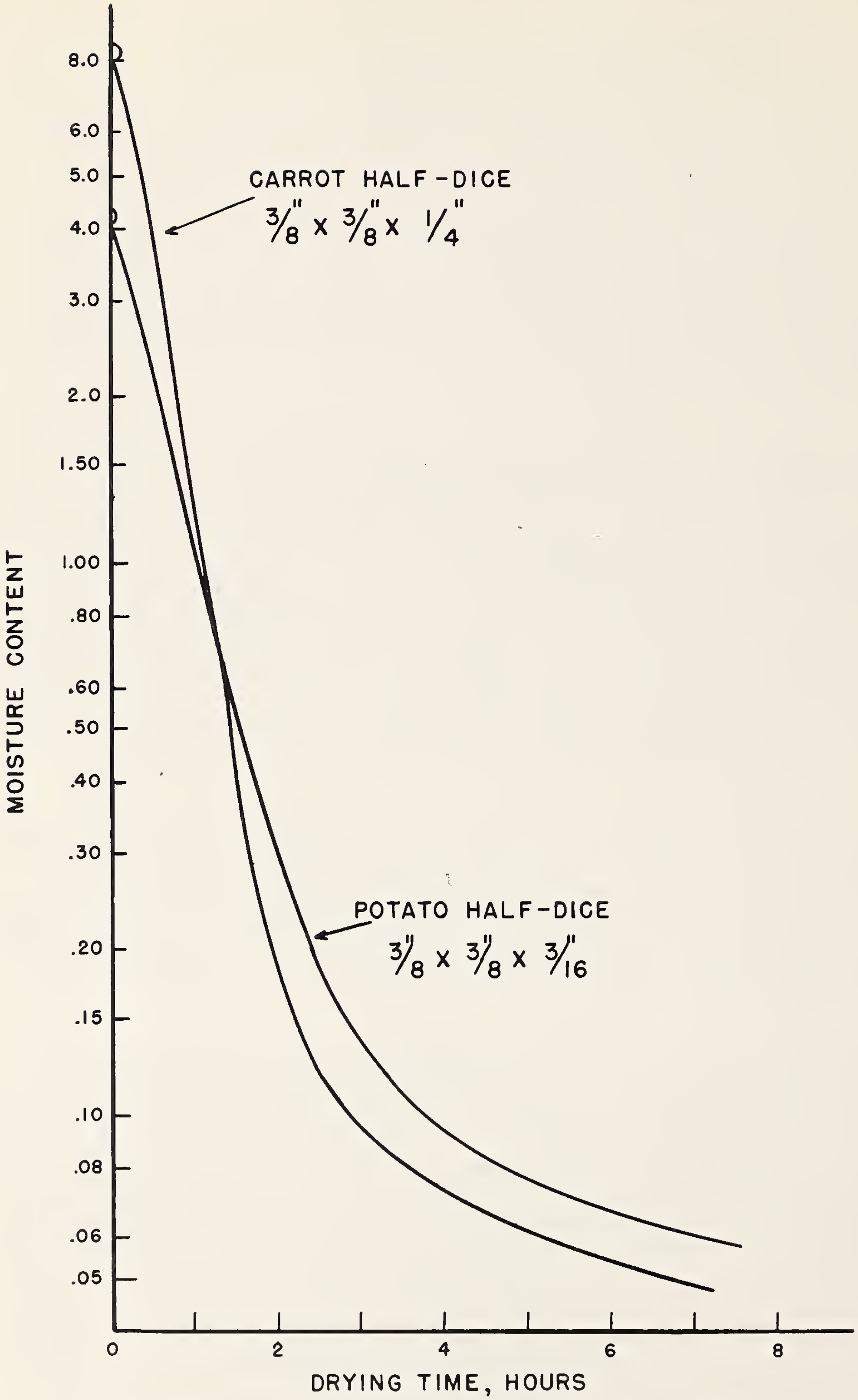

FIGURE 18-DRYING CURVES FOR CARROT AND POTATO HALF-DICE

Differences in the composition of the vegetable are known to have an effect on the drying rate. Blanched (scalded) material dries more rapidly than the same material unblanched, perhaps because the scalding kills the tissue and thereby increases its permeability to moisture movement from the inside to the surface. The leaching of sugars and other soluble constituents which may occur during the blanching, washing, or fluming of the cut pieces also may increase the drying rate in the low moisture end of the drying curve. A. H. Brown and his associates at the Western Regional Research Laboratory compared the drying rates of potato pieces varying widely in sugar content (produced by varying the conditions under which the raw stock was stored) and found[12] that while the drying rates were unaffected by sugar content down to a level of about T = 0.3 pounds moisture per pound of dry solids, the drying time from T = 0.3 to T = 0.075 was greater the higher the sugar content. For the material he was using, Brown determined that the drying time in this low-moisture range was approximately proportional to either one of the following two expressions: [1 + 0.059 (% total sugar)] , or [1 + 0.12 (% reducing sugar)] . The sugar content is here expressed as percentage of the weight of dry solids. The experimental data were not extensive enough to determine which of these expressions is the more generally useful.

III-H. Effect of the Shape and Size of Pieces

The only directly comparable published data on rates of drying of vegetable, pieces differing in size are those determined by Ede and Hales.[13] Figure 19, reproduced from their bulletin, shows drying curves for Julienne strips of potato of three different sizes. The drying was carried out on large trays, the back edges of which dried materially slower than the front edges; the curves shown are for the material near the front edges of the trays. The trays were loaded at 1.5 pounds per square foot, air speed was 960 feet per minute, the temperature was 158°, and the wet-bulb temperature 95°.

From this illustration it is plain that a small difference in the thickness of vegetable pieces can cause an altogether disproportionate change in the drying time. A difference is evident at all stages of drying, but is far more marked in the low-moisture range than near the beginning. This is what would be expected, from what is known about the principles of drying. During the initial phases, as we have already seen, the rate of evaporation per unit of surface remains substantially constant. Now suppose that we compare a single cube with two halves cut from a similar cube. The weight of dry solids in the two halves will be the same as in the whole cube, but their combined surface will be 33 percent greater. Their initial drying rate, in terms of pounds of water per hour per pound of dry solids, should be greater than that of the cube in about the same proportion.

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[12] Unpublished report dated November 10, 1943.

[13] See first footnote, page 46.

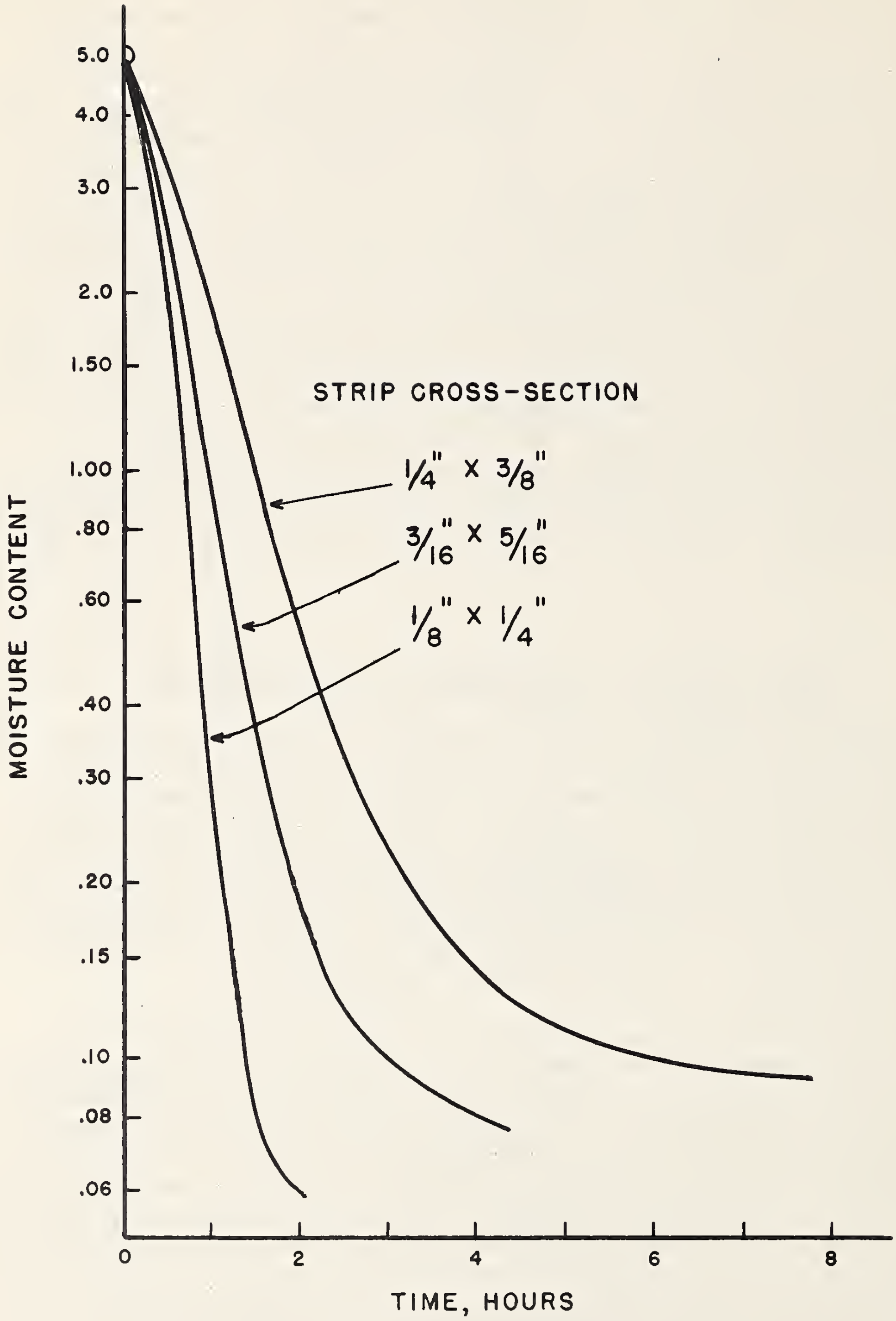

FIGURE 19-EFFECT OF PIECE SIZE ON DRYING TIME

Next, assume that we compare six separate cubes with six similar cubes put together to form a "strip" six times as long as it is thick. By the same kind of reasoning we can infer that the initial drying rate of the cubes will be some 38 percent greater than that of the strip.

In the later phases of drying the thickness of the solid substance through which water must diffuse will become the controlling factor. The mathematical theory of diffusion predicts[14] that the time required to produce a certain fractional fall in moisture content under diffusional control varies as the square of the thickness; that is, for example, 9 times as long will be required for a given amount of drying if the piece is 3 times as thick. Note, however, that the original dimensions of the wet pieces do not count; it is the thickness of the nearly dry pieces that is important, as was stated in the paragraph above which compared the drying of carrot pieces and potato pieces. In view of the extreme distortion of vegetables upon drying, and sometimes the formation of internal shrinkage holes, there is no point in attempting theoretical calculation of comparative drying rates in the low moisture range.

Drying times may actually be reduced to a few seconds if the piece size is reduced far enough. That is the physical basis for the processes of spray drying and air-suspension drying. Dry products which show no evidence whatever of scorching, or "heat damage", can be made. However, these products have a somewhat specialized usefulness; excellent mashed potatoes can be prepared, but not fried potatoes; good scrambled eggs, but not eggs sunny side up.

In the opposite direction, the reason why whole carrots or quartered potatoes are not commercially dehydrated must be apparent--the drying time would be so long as to be completely impractical, even if a reasonably good final product could be made, which is doubtful. The sizes into which vegetables are cut for commercial dehydration represent a compromise between the need for rapid drying and the desire to serve the final consumer large pieces of the products.

III-I. Effect of the Barometric Pressure

The experiments upon which published drying rates are based were all conducted in locations not far above sea level, and hence at approximately the sea-level normal barometric pressure, 29.92 inches of mercury. The effect of a substantially lower pressure, such as prevails in Idaho or Colorado, can, however, be predicted with some assurance from general physical principles. It is not a very marked effect.

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[14] See Walker, Lewis, McAdams, and Gilliland. Principles of Chemical Engineering, 3rd Edition, 1937, pp. 642-657.

Regardless of the barometric pressure, the temperature of moist material in a dehydrator will at first follow closely the indications of a wet-bulb thermometer installed in the same air stream, and then will gradually rise nearly to the dry-bulb temperature of the air. The piece temperature, and so also the vapor pressure of the moisture in the piece, will therefore be determined by the wet- and dry-bulb controls at low barometric pressures, just the same as at high pressures. As we have seen in a preceding section of this bulletin, however, the air humidity (either absolute or relative) corresponding to a given combination of wet- and dry-bulb temperatures does change as barometric pressure changes. That means, in accordance with the definition of relative humidity (equation 1), that the partial pressure of water vapor in the air also will change. Since the driving force for surface evaporation is proportional to the difference between the vapor pressure of the moisture at the surface of the piece and the partial pressure of water vapor in the air, the rate of evaporation will decrease if this difference becomes smaller.

Consider now a specific case of drying at a dry-bulb temperature of 160° and a wet-bulb temperature of 100°, but under a barometric pressure of only 23.92 inches of mercury (corresponding to an altitude of about 5900 feet) instead of the normal 29.92 inches. While the material is still wet its temperature will be close to 100°, and the vapor pressure of the water in its surface layer will be substantially that of pure water at 100°, or 1.933 inches. The standard sea-level humidity chart shows for the given dehydrator temperature conditions a relative humidity of 13.5 percent; the vapor pressure of water at 160° is 9.65 inches; therefore at sea level the partial pressure of water vapor in the air would be 1.303 inches and the driving force for evaporation would be 0.63 inches of mercury. But reference to a humidity chart drawn for a barometric pressure of 23.92 inches (or calculation by the procedure outlined earlier in this bulletin) shows that at this lower pressure the given temperatures correspond to a relative humidity of 14.8 percent. The partial pressure of water vapor in the air is therefore 1.430 inches, and the driving force is only 0.503 inches. Then the initial rate of evaporation should be only about 80 percent as rapid at 5900 feet elevation as at sea level, at these assumed values of wet- and dry-bulb temperature. A wet-bulb temperature of about 98°, instead of 100°, would be required to produce the same rate of initial evaporation.

More important, however, in fixing the effect on the total drying time is the influence the barometric pressure may have on the rate of drying in the low-moisture range. Here we find that the main rate-determining factor, the rate of internal diffusion of the moisture, should be nearly unaffected by the change in barometric pressure; the diffusivity is controlled only by the moisture content of the piece and its temperature--and the latter will be substantially the same as the dry-bulb temperature of the air. A slight effect will remain, however. At the higher partial pressure of water vapor in the air (1.430 inches as compared with 1.303 inches, in the above example) the equilibrium moisture content of the product will be a little higher (roughly, about 2.5 percent instead of 2.3 percent). If one were trying to dry the product almost to this equilibrium value the time required would be substantially longer, but if the end point is to be an average moisture content of, say, 6 percent the additional time required will be negligible.

It will be noted that the effect of a lower barometric pressure is to require a little greater wet-bulb depression to produce the same drying rate. The result points up a fallacy which is believed by some dehydrator designers and operators, namely, that more rapid drying can be assured if the air circulating fan and dampers are placed so that the drying compartment will be under "suction"--that is, below the outside atmospheric pressure, rather than above it. The arrangement may have its advantages for other reasons, but not for that one. In the first place, the "suction" produced by the types of circulating fan used in dehydrators is negligible in comparison with the atmospheric pressure; the pressure in the dehydrator would be reduced at most only a few tenths of an inch of mercury. The effect on drying rate, however slight, is in the opposite direction--a slowing of the rate--if the dehydrator temperatures are maintained unchanged.

This is not to say that true vacuum drying will not be effective. It can be extremely effective and rapid in a well designed vacuum drier. But under the conditions of real vacuum drying, for example at a pressure in the drier of only an inch or two of mercury, wet-bulb temperature ceases to have a practical meaning and drying rates are mainly fixed by the rate at which heat can be safely supplied to the product by means of conduction from the trays or by radiation.

IV. DRYING CONDITIONS WITHIN A DEHYDRATOR

This chapter describes the changes in temperature and humidity which occur in air passing through a dehydrator, presents methods for estimating the drying time and capacity of a dehydrator, and a method for estimating the heat requirement of a dehydrator.

The foregoing sections of this bulletin have discussed the principles of the evaporation of moisture, and the results of experiments on the factors which influence the rate of drying of fruits and vegetables. We now have to consider the physical processes which occur in the dehydrator itself. As in the preceding sections, the main emphasis of this discussion will be placed on hot-air dehydrators of the tunnel type--either the truck-and-tray variety or the through-flow conveyor variety.

The conditions of commercial vegetable dehydration contrast with the simple conditions of the drying experiments described above in a number of ways, particularly in that the air temperature and humidity in commercial dehydrators change markedly as the drying of the material progresses. The air velocity will also change somewhat as a consequence of these temperature and humidity changes and the shrinkage of the product, or it may be changed purposely at some stage of the process. Both the drying time and the quality of the product are affected by the manner in which these changes occur.

IV-A. Cooling of Air Due to Evaporation of Moisture

The heat required to evaporate water is supplied, in all common types of hot-air dehydrators, by the circulating air itself. The heat absorbed in producing the evaporation is taken away from the air; consequently the dry-bulb temperature of the air falls. This cooling effect is very substantial. As a rough average for commercial conditions, when 1000 pounds of air take up 1 pound of water vapor by evaporation the air cools 5° F.[1] Thus, unless additional heat is supplied along the way, the air leaving the drying section of a dehydrator is always cooler than the air entering the section.

Theoretically, the air will not cool quite 5° when evaporation raises its absolute humidity by 0.001 (that is, an increase of 1 pound of water vapor per 1000 pounds of dry air), as is shown by the following calculation:

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[1] W. B. Van Arsdel. Tunnel dehydrators and their use in vegetable dehydration. Food Indus. 14(10):43-46; (11):47-50; (12):47-50 (1942).

ould read: "of the pound of water vapor from 95° up to the new dry-bulb temperature of the air, which will be (closely enough) 5° lower than 160°, or 155°."

Assume that 1000 pounds of air, having a dry-bulb temperature of 160° and a wet-bulb temperature of 95°, evaporates 1 pound of water which is already at the wet-bulb temperature, 95°. The latent heat of evaporation of water at 95° (from the curve on the humidity chart, Figure 3) is 1,040 B.t.u. per pound. In addition to this heat of evaporation, the air must also supply the smaller amount of heat required to raise the temperature of the air, which will be (closely enough) 5° lower than 160° or 155°. From the humidity chart, the initial absolute humidity of the air at 160° and 95° was 0.021; the initial 1000 pounds therefore contained 21/1.021, or 20.55 pounds of water vapor and 979.45 pounds of dry air; its humid heat (equation 7, page 22) is 0.249 B.t.u. per pound of dry air. Since the specific heat of water vapor is 0.47 B.t.u. per pound, the 1000 pounds of air must furnish 0.47 (155° - 95°), or 28 additional B.t.u. to warm the water vapor from 95° to 155°; the air must supply a total of 1068 B.t.u. of heat. Its temperature will therefore fall

$$\frac{1,068}{979.45 \times 0.249} = 4.4^\circ \text{ F.}$$

The new absolute humidity of this air is very nearly 0.022. If we refer to the humidity chart, air of this absolute humidity and a dry-bulb temperature of 160° - 4.4°, or 155.6° has a wet-bulb temperature of just 95°. That is, this process of evaporation of water, in which the air itself supplies all the heat required, cools the air, but <u>leaves its wet-bulb temperature unchanged</u>. This is an extremely important general rule, because it implies that the wet-bulb depression of air passing through the drying section of a dehydrator becomes smaller and smaller as the air produces more and more evaporation from the wet material.[2]

Actually, the conditions assumed for this example are never fully realized under practical conditions. In addition to supplying heat for evaporation, the circulating air must also supply the heat required to warm the incoming trucks and trays (and eventually also the nearly dry product) up to the dry-bulb temperature, and the wet material up to the wet-bulb temperature. Some heat will always be lost to the surroundings by conduction through the dehydrator walls; some heat may be gained by conduction through the wall of an adjoining furnace compartment. In the common types of tunnel dehydrator, drying fruits or vegetables, the air cools nearer 5° than 4.4° for a rise of 0.001 in absolute humidity, and the wet-bulb temperature also falls a few tenths of a degree--or, if the walls are not well insulated, as much as a degree or two in its passage

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[2] The process of evaporation we have just described, in which the drying air itself furnishes all the necessary heat, is known as "adiabatic evaporation". The term "adiabatic" signifies that no heat is gained from or lost to the surroundings during the process. The method of calculation of wet-bulb temperature lines on humidity charts (as described in section I-G of this bulletin) actually gives adiabatic evaporation lines; it is only a happy coincidence that in the case of the evaporation of water, wet-bulb temperature lines are so nearly the same that they can be used for practical purposes interchangeably. If it were some other liquid that was being evaporated, say alcohol, this would not be possible.

through the entire length of the drying section. If the material to be dried contains much less moisture than fruits or vegetables do, or is loaded so lightly that the heat required to warm up trucks and trays or conveyors becomes an appreciable part of the total requirement, the simple rule of a constant wet-bulb temperature will fail, and more complicated methods of calculation will be necessary. It will also fail completely if heat is supplied to the drying material by radiation (as in an infra-red drier), of if the air is reheated during its passage through the drying section; in either of these cases the wet-bulb temperature of the air will rise. In the following paragraphs we shall make the assumptions (unless otherwise specifically stated) that a rise of 0.001 in absolute humidity corresponds to a fall in dry-bulb temperature of 5°, and that the wet-bulb temperature of the air does not change in the drying section of the dehydrator.

Let us consider now the most widely used type of fruit or vegetable dehydrator, the truck-and-tray tunnel. The preheated drying air enters one end of the long drying chamber, whose cross-section is just wide enough to accommodate a string of trucks, or dollies, each of which bears trays of the product stacked nearly to the ceiling of the tunnel; the air leaves the drying section at the other end of the chamber,[3] after having passed through the spaces between trays along the whole string of trucks. Periodically a truckload of dry product is removed from one end of the tunnel, the whole string of trucks is moved along one space, and a truckload of wet material is inserted into the now vacant space at the other end. This is what is called a "progressive" tunnel. It is almost equivalent to a continuous, steady flow of wet material into one end of the tunnel and a corresponding continuous withdrawal of dry product from the far end. For the sake of simplicity we shall regard the flow of product as truly continuous, reserving discussion of the minor effect of the "progressive" movement of trucks to a later paragraph. Manifestly, two simple arrangements of such a tunnel are possible--one in which the hot air enters the same end of the tunnel as the wet product, and one in which it enters at the end where the dry product is withdrawn. The first is designated "parallel-flow", or "concurrent" drying, the second is called "counterflow" drying.

In a continuous tunnel the following very simple and useful relationship exists:

> The change in air temperature between any two points along the tunnel is proportional to the change in the moisture content of the product (dry basis) between the same two points.

The factors which govern the ratio of the two changes are given in the following equation:

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[3] If a two-stage dehydrator is being used, the two sections must be considered separately.

$$ {}_1t_d - {}_2t_d = \pm \frac{83\ S\ L_o}{G\ \theta_h\ (T_o + 1)} (T_1 - T_2)\ {}^{4/} \quad - \quad - \qquad (9) $$

(+ sign for parallel-flow, - sign for counterflow drying).

${}_1t_d$ and ${}_2t_d$ are the air dry-bulb temperatures at points 1 and 2 respectively in the drying section.

T_1 and T_2 are the moisture contents (dry basis) at the same two points.

S is the total area of tray surface in the dehydrator, square feet.

L_o is the initial tray loading, pounds of wet material per square foot of tray surface.

G is the flow of air through the tunnel, pounds of dry air per minute.

θ_h is the total length of time, in hours, that a piece of the product remains within the tunnel.

T_o is the initial moisture content (dry basis) of the material as it enters the tunnel.

For example, suppose that a certain counterflow tunnel dehydrator holds 10 trucks, each stacked with 30 3-ft. x 6-ft. trays, so that the total tray surface in the tunnel is 5400 square feet, and that carrot dice with an initial moisture content $T_o = 8.4$ are loaded on the trays at $L_o = 2.0$ pounds per square foot. Suppose, further, that air flows through the tunnel at the rate of 3000 pounds per minute, and that each truck remains in the tunnel for 8 hours. What will be the difference in air temperatures between the point where the air leaves the tunnel (where the wet product enters, $T_1 = 8.4$) and the point where the moisture content of the product, $T_2 = 0.10$? Applying equation 9, the difference in air temperatures will be 33°.

While this direct relation between evaporation and change in air temperature holds just as truly in a "progressive" and discontinuous movement of trucks as in a continuous flow of product through the dehydrator, the application of the principle is more complicated for the former. Only a brief discussion is necessary here, however, because in common commercial types of dehydrator the effect upon the overall performance of the drier is relatively small.

Consider a parallel-flow tunnel, built to hold only a relatively small number of trucks, say 6. Then the trucks remain stationary for successive intervals of one-sixth of the total drying time. When a fresh truck-load of wet material is placed in the tunnel the hot air at first spends much of its energy in heating up the truck, trays, and wet product, and the temperature of the air passing down through the tunnel drops sharply.

4/ This equation is simply another way of saying that 1000 pounds of air cools 5° when 1 pound of water evaporates into it. SL_o/θ_h is the weight of wet material supplied to the tunnel per hour; multiplying this weight by $(T_1 - T_2)/(T_o + 1)$ gives the weight of water evaporated between points 1 and 2 per hour; dividing this figure by 60G gives the weight of water picked up by a pound of air. The numerical factor 83 is 5 x 1000/60.

The heating-up period passes quickly, but is succeeded by extremely rapid evaporation from the new truck-load; air temperatures throughout the tunnel remain relatively low. But if we are dehydrating fruits or vegetables the period of rapid evaporation hardly lasts for one-sixth of the total drying time, and air temperatures down through the tunnel will rise appreciably before the time comes to insert another fresh truck. The result, as it might be reflected on a temperature record at the air exhaust end of the tunnel, is a "sawtooth" variation, as shown in Figure 20.

Rather more significant is the variable air temperature to which any portion of the product will be exposed during its stay in the tunnel. Figure 21 shows what the conditions would be for two pieces of product passing through a 6-truck parallel-flow tunnel, one of the pieces being located near the front edge of a tray (closest to the hot air intake) and the other near the back edge. Much of the drying takes place in the first truck position, and the material near the front of the trays is always exposed to more severe drying conditions than material toward the back edge.

Figure 22 is a comparable diagram showing the air temperatures that might be experienced by material dried in a 6-truck counterflow tunnel. The sawtooth effect is much less pronounced, and there is less difference between the temperature experiences of front and back positions on the trays.

Note carefully that θ_h, the factor of time in equation 9, means only the length of time the material stays in the dehydrator. It is what is called a "retention" or "residence" time. It does not necessarily have any relation to the time required to dry the product to a certain final moisture content, for obviously it would be possible to push trucks through a dehydrator so fast that they would come out almost as wet as they went in. We shall see later that the practical use of all these calculations depends upon making this "retention time" equal to the "drying time" as found from experimental drying rate studies.

While the same general principles apply to air temperature changes in a conveyor dehydrator as in a tunnel-and-truck dehydrator, their application is so much more complicated that the system can be described here in only the most general terms. The most widely used form of conveyor dehydrator circulates the drying air through the layer of moist pieces carried by the perforated conveyor, recirculates most of the air over heating coils, and is divided into three or four sections in which the air temperature can be independently controlled. In each of these sections, however, the air above and below the conveyor is more or less thoroughly mixed. At the wet end of the dehydrator the air which leaves the layer of wet material is relatively cool and nearly saturated; if the air is blown up through the conveyor in this section, as is usual, the material on the bottom of the layer will dry rapidly, that near the top of the layer only slowly. As the material progresses through the first section the rate of drying in the bottom layer will decrease,

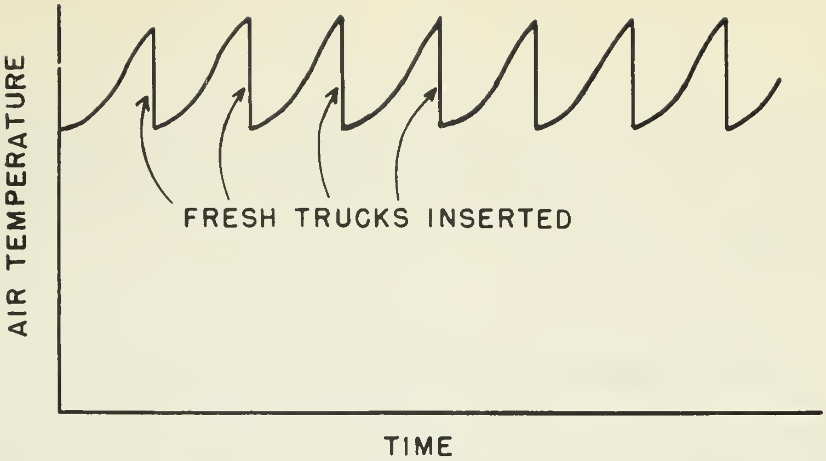

FIGURE 20-FLUCTUATION OF COOL-END TEMPERATURE IN PARALLEL-FLOW TUNNEL

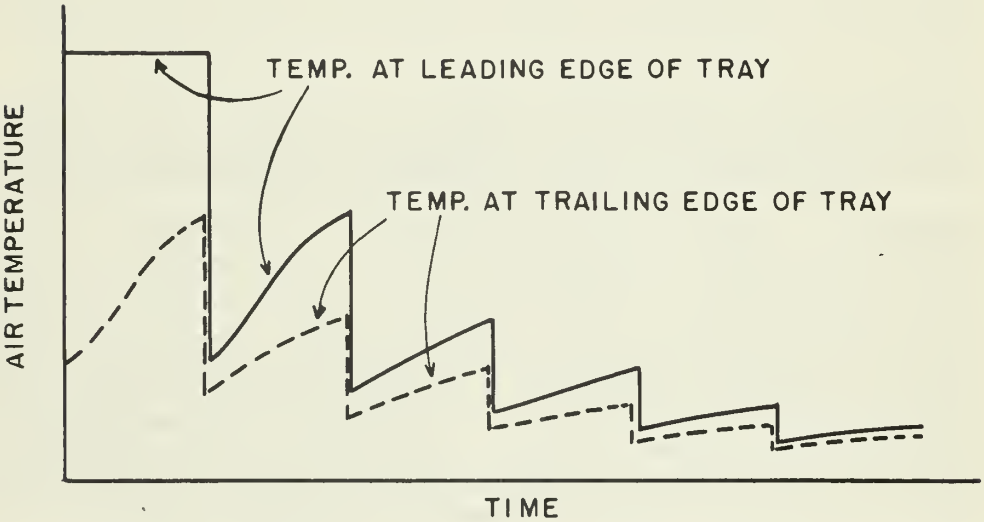

FIGURE 21-PARALLEL-FLOW TUNNEL-FLUCTUATION OF AIR TEMPERATURE AT THE PRODUCT

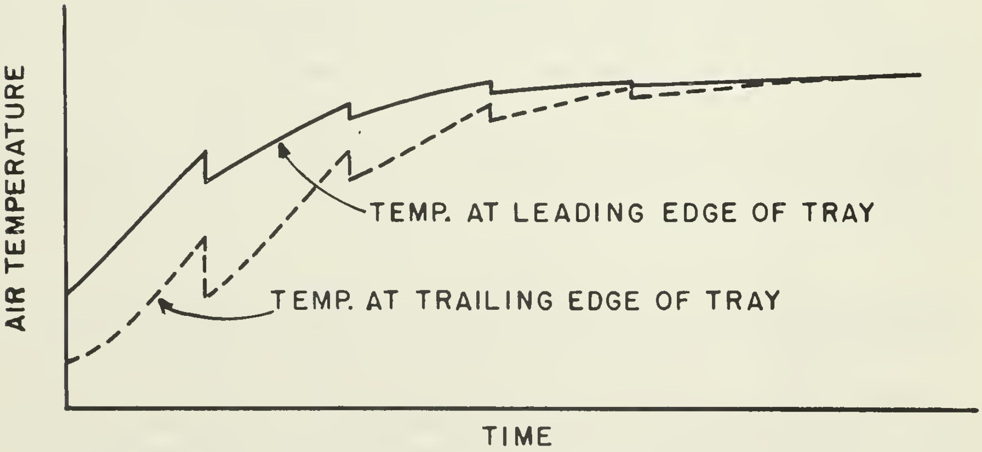

FIGURE 22-COUNTERFLOW TUNNEL-FLUCTUATION OF AIR TEMPERATURE AT THE PRODUCT

hotter air will reach the upper layers, and they will start to dry faster. If the direction of air flow is reversed in the second section, the more moist top layer will now dry rapidly and the bottom layer only slowly. No quantitative studies of the way these factors interact have ever been published.

IV-B. Maximum Evaporative Capacity of a Tunnel Dehydrator

In preceding sections of this bulletin we have seen three significant facts which should now be brought together: (1) The dry-bulb temperature of the air falls as moisture evaporates into it; (2) the wet-bulb temperature of the air remains substantially constant; and (3) the drying rate becomes smaller as the difference between dry-bulb and wet-bulb temperatures becomes less, and sinks to zero even before these two temperatures become equal.

In combination, these facts enable us to estimate very quickly the maximum drying capacity of a tunnel dehydrator. It is that amount of evaporation which will reduce the wet-bulb depression to zero.

Suppose that, as in the preceding example, 3000 pounds of air per minute pass through the tunnel, and that the air enters with a dry-bulb temperature of 160° and a wet-bulb temperature of 90°. Reduction of the dry-bulb temperature also to 90° would correspond to the evaporation of about (160 - 90)/5, or 14 pounds of water per 1000 pounds of air; that is 42 pounds per minute, or 30.2 tons of water evaporated in 24 hours. Given the specified air flow and those initial air temperatures even the fastest-drying product could not lose more moisture than that. Increasing the air flow, however, or increasing the initial wet-bulb depression, will increase the evaporative capacity proportionally.

IV-C. Experimental Determination of Probable Drying Time

We can now define a procedure which will enable us by means of small-scale tests to obtain a good estimate of the drying time for a particular product in a truck-and-tray tunnel of known characteristics. The tests will also furnish product samples whose quality (as affected by drying conditions) will be similar to the quality of material dried in the tunnel.

A well-designed experimental cabinet drier is required for this purpose.[5] A cabinet drier is one in which only a single tray, or group of trays, of the material is dried as a batch; the air temperature, humidity, and

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[5] Sketches, designated C-112 and C-113, of a cabinet drier which has given satisfactory service are obtainable upon request addressed to the Western Regional Research Laboratory, Albany, California.

velocity are, however, independently controllable by the operator. For this purpose only a single trayload will be used, and the drier should be designed so that the ratio of air flow to evaporation will be very large, since then the change in air temperature across the tray will be only slight. Moist material, prepared exactly as it would be for commercial dehydration, will be spread on a tray of the type to be used in the tunnel (although smaller than the commercial tray). The air velocity across the tray in the cabinet will be adjusted to equal the expected air velocity between trays in the tunnel.[6] The tray will be so arranged that it can be quickly and accurately weighed at intervals, in order to keep a running check of the moisture content of the material on the tray. The moisture content of average samples of the material before and after drying will be determined, so that the tray weighings can finally be accurately translated into terms of moisture loss per pound of dry solids.

The test procedure can be explained most simply by means of an example. Suppose that carrot dice are to be dehydrated in a counterflow truck-and-tray tunnel which will hold ten truckloads, each with a tray area of 540 square feet. The prepared carrot dice, with an initial moisture content of T_0 = 8.40, are to be spread on metal-screen trays at a loading of 2.0 pounds per square foot. The circulating fan is to supply 40,000 cubic feet per minute of air at 160° and a wet-bulb temperature of 95° to the hot end of the tunnel. The carrots are to be dried to a final moisture content of 5.0 percent (T_f = 0.053). What will be the drying time, and what will be the 24-hour daily output of dry product?

First, we shall estimate, roughly, that the air temperature may fall to 110° at the "wet end" of the tunnel; its volumetric flow there would be about 37,000 cubic feet per minute (by equation 6, page 21). Now if the free area around the trucks and between loaded trays is, say, 33 square feet, the air velocity in the "wet end" should be 1120 feet per minute. We shall use that air velocity in our cabinet drier tests.

Next, from the humidity chart we find that the absolute humidity of the hot air supply is 0.0210. Therefore (again from equation 6) the humid volume is 16.2 cubic feet per pound of dry air, and the mass air flow through the tunnel is 2465 pounds of dry air per minute. We shall use this figure in equation 9, which expresses the relation between evaporation and fall in air temperature.

Now our immediate object is to plan a schedule of change for the air temperature in the test run that will simulate the temperature change in the tunnel (disregarding the "sawtooth" effect described in the preceding section, and assuming that the tunnel will act like a

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[6] Shrinkage of the material on the trays and changes in air temperature and humidity both produce a change in air velocity along the tunnel. Since, however, air velocity has a substantial effect on drying rate only in the range of relatively high moisture content, air velocity in the cabinet will be approximately matched with the velocity to be expected in the "wet end" of the tunnel.

continuous drier). But we do not yet know what retention time in the tunnel will produce drying to a final moisture content of 5 percent, so we cannot determine yet what the fall in air temperature will be. The difficulty is resolved by making a minimum of two, and preferably three, test drying runs which will bracket the unknown true figure. This can be accomplished as follows:

We know from the form of equation 9 (page 69) that if the air temperature at points along the tunnel is plotted on coordinate paper against the moisture content of the product at the same points a straight line will result. Let us therefore set up such a diagram, as in Figure 23. We know the point at one end of the line--temperature 160°, moisture content 0.053--and the moisture content, 8.40, but not the temperature at the other end. We assume three different temperatures, say 100°, 110°, and 120°, in the expected range, and draw the three corresponding straight lines. Each one of these lines gives us a schedule for conducting one of the test drying runs; the temperature in the drier will be raised in accordance with the moisture content remaining in the material on the tray, as estimated from periodical weighings of the tray. The wet-bulb temperature of the air will be maintained unchanged at 95° from beginning to end of the run. Weighings and air temperature adjustments cannot, of course, be made continuously, but the desired straight line relationship can be closely approximated in a series of small steps, as indicated on one of the lines in Figure 23.

The three test runs will give us three different values of the time required to dry the product down to a moisture content of 5 percent; the lower the wet-end air temperature, the longer this time will be. The three drying times will be plotted, as in Figure 24, against the wet-end air temperature. On the same diagram we shall plot another curve, showing retention time; this we can derive from the following form of equation 9:

$$t_d' - t_d'' = \frac{83\ S\ L_o}{G\ \theta_h (T_o + 1)} (T_o - T_f) \quad - - - - - \quad (10)$$

Here t_d' is the hot-end air temperature and t_d'' the cold-end air temperature.[7] If we insert the numerical values of our example, this reduces to:

$$160 - t_d'' = \frac{83 \times 5400 \times 2}{2465 \times 9.40\ \theta_h} (8.40 - 0.053) = \frac{323}{\theta_h} \ .$$

For a cold-end temperature of 100° this gives a retention time of 5.38 hours; for 110°, 6.46 hours; and for 120°, 8.07 hours. These are the points which determine the retention time curve in Figure 24.

Now the point at which the drying time and the retention time curves cross gives us the values we have been seeking--namely, a cold-end

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[7] In a counterflow tunnel the "cold end" is also the "wet end".

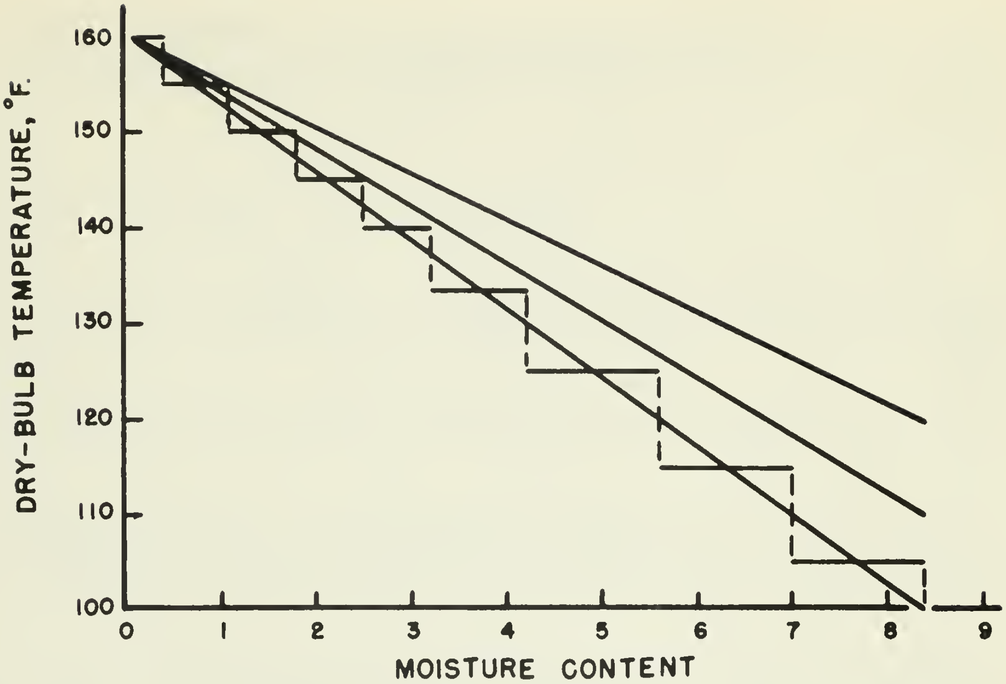

FIGURE 23–DIAGRAM USED FOR SCHEDULING EXPERIMENTAL DRYING RUN

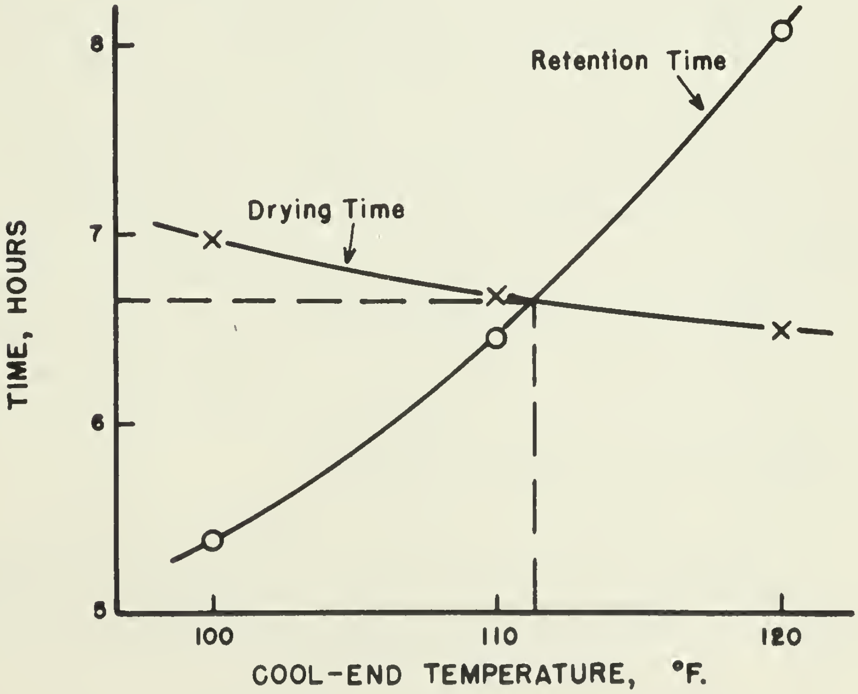

FIGURE 24–ESTIMATION OF DRYING TIME FOR SPECIFIED TUNNEL CONDITIONS

temperature of 112°, and a time of 6.65 hours. Retention of the product in the tunnel for that length of time (that is, inserting a fresh truck about every 40 minutes) will, we estimate, just dry it to 5 percent moisture. The 24-hour output of dry product should be,

$$\frac{5400 \times 2 \times 1.053 \times 24}{9.40 \times 6.65} = 4375 \text{ pounds.}$$

The same kind of procedure can be used to predict the behavior of a two-stage tunnel, such as the widely used combination of a parallel-flow first stage and a counterflow finishing stage. A more elaborate series of test runs must be made, however, because the moisture content of the product at the point of changeover from first to second stage will not be known in advance.

Estimates of drying time and capacity made in this way should, of course, be so discounted as to allow for the imperfections of ordinary dehydrator operation, such as useless short-circuiting of the hot air and uneven loading of trays.

The experimental procedure used for predicting drying time and capacity of a conveyor dehydrator must, of course, be quite different from the method just described. A through-flow experimental drier will be used. The perforated support will be similar to the perforated conveyor. The volume of air flow per square foot of supporting surface will be made equal to that expected in the commercial drier; the direction of air flow must be reversible, and the temperature and humidity of the air be controllable by the operator. Temperature and humidity conditions must be chosen in advance for each of three or four phases of the test run corresponding to the separate sections of the conveyor dehydrator. These drying conditions will be kept constant during each phase. The times of exposure in each phase will be made equal to the times the product will remain in the different sections of the dehydrator for some one chosen value of the rate of travel of the conveyor. If, as is sometimes done, the product is to be dumped from one conveyor onto a slower moving one, a similar mixing and respreading will be done in the experimental unit. Ordinarily three such runs will be required, corresponding to three different rates of conveyor travel. When the moisture contents of the final products of the experimental runs have been determined the proper conveyor speed (and therefore drying time and dehydrator capacity) can be estimated by plotting the results.

It is apparent from the foregoing paragraph that a large number of test runs must be made if various combinations of temperature and humidity in the different sections of the drier are to be tried--for example, to find the combination which gives the highest production of acceptable dried product.

IV-D. Estimation of Tunnel Dehydrator Capacity from Standard Drying Rate Data

The procedure described in the preceding section is, of course, laborious. If a product of unusual shape, size, or composition is to be dried, and something better than a mere guess about dehydrator capacity is needed, the expenditure of effort may be well justified. However, for many purposes published data on drying rates, for example the AIC-31 series of bulletins or the Ede and Hales bulletin referred to on page 46, provide the basis for a sufficient answer, no further experimental work being necessary.

The AIC-31 nomographs are applied to estimation of truck-and-tunnel dehydrator capacity by using a procedure basically the same as that described for experimental test runs A group of three cold-end temperatures is chosen to bracket the expected true value. For each one the straight-line relationship between air temperature and moisture content is plotted, and each of the straight lines is broken down into a series of short constant-temperature steps. The nomographs are then used to obtain three estimates of the drying time, each total being the summation of the fractional times estimated for the temperature steps. The three drying times are plotted against cold-end temperature on a diagram which also carries a curve of retention time versus cold-end temperature, calculated as described above. The intersection of the two curves provides the desired estimate of drying time under the specified tunnel conditions.[8/] Unpublished studies made by the technologist of a commercial dehydration plant have indicated that a satisfactory approximation to the actual drying time in the plant can be obtained by this method The investigators at the Western Regional Research Laboratory believe that the exact kind of raw material, actual average size of pieces, uniformity of tray loading, design of trays, and possibly other factors in their experiments are so unlikely to be duplicated in commercial operation that drying time estimates taken from the nomographs should not be expected to check with commercial drying times closer than perhaps plus or minus 20 percent. On the other hand, the nomographs may be used with confidence for quick estimates of the result of almost any proposed change in operating conditions, as discussed more fully in the second paragraph below.

Guillou[9/] has shown that the drying characteristics of prunes are such that the drying time in a counterflow dehydrator can be estimated in a considerably simpler way. Drying rate is proportional at all times to the "free moisture content" (that is, the amount of moisture in excess of the apparent equilibrium moisture content); the constant of proportionality can be determined from an equation which contains the

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[8/] W. R. Marshall, Jr., The drying of food, Heating, Piping, and Air Condg., 15(11):567-572, Nov. 1943, describes a radically different method of estimating drying time and applying the result to dehydrator design

[9/] See reference, page 46.

factors of air temperature, humidity, and velocity, and the size of the fruit. Guillou applied these known relations to the design of a prune dehydrator which will operate at minimum cost.

Calculations of this kind will produce a wide range of useful information about the performance of a tunnel dehydrator. For instance, the tray loading which will give the maximum dry output for a given dehydrator can be determined for the standard products whose drying rates have been investigated--and if the information is carefully analyzed the result can be extrapolated with some confidence to a material prepared in different sized pieces or otherwise somewhat different. Or the probable effect on capacity of changing the hot-end temperature, or the wet-bulb temperature, or the air discharge from the fan, or of operating the tunnel parallel-flow instead of counterflow, or of changing the number of trucks in the tunnel, or of stopping the drying at a higher level of final moisture content--all can be estimated very quickly. These estimates will provide a basis for determining in advance the probable effect of any proposed change in dehydrator operation on the plant operating costs.

IV-E. Recirculation of Air in Dehydrators

The air leaving the cool end of a dehydration tunnel is likely to have a temperature of at least 110°, and may be much hotter than that. A very substantial saving in heat can be made by letting only a part of this air escape and mixing the remainder with the fresh air going to the heater. This is "recirculation", and it is practiced in most commercial dehydrators, not only to save heat, but also to provide a simple means of controlling the wet-bulb temperature of the circulating air.

It may seem puzzling that any of this relatively cool, moist air can serve a useful purpose if returned, but study of typical operating conditions discloses that it is possible to recirculate a substantial proportion, sometimes as much as three-quarters, of the circulating air in commercial tunnel dehydrators and realize a considerable saving in the cost of heat without serious loss of tunnel capacity. Figure 25 illustrates the situation on a skeleton humidity chart. Point S represents the temperature and humidity of the fresh air. Designating the desired hot-end dry-bulb temperature by the line t', then point U represents the condition of the air entering the hot end without recirculation; its absolute humidity is the same as that of the fresh air. In passing through the tunnel its temperature will fall and its absolute humidity will rise, as shown by the line UV, which is parallel to the wet-bulb temperature lines of the chart.

If there is no recirculation, all of the air which has come to the conditions of the point V will be discarded, and more fresh air will be heated from S to U. But if, say, only one-quarter of the exhaust air is discarded, and only that difference is made up with fresh air, then humidity rises throughout the tunnel, and after a short time new steady

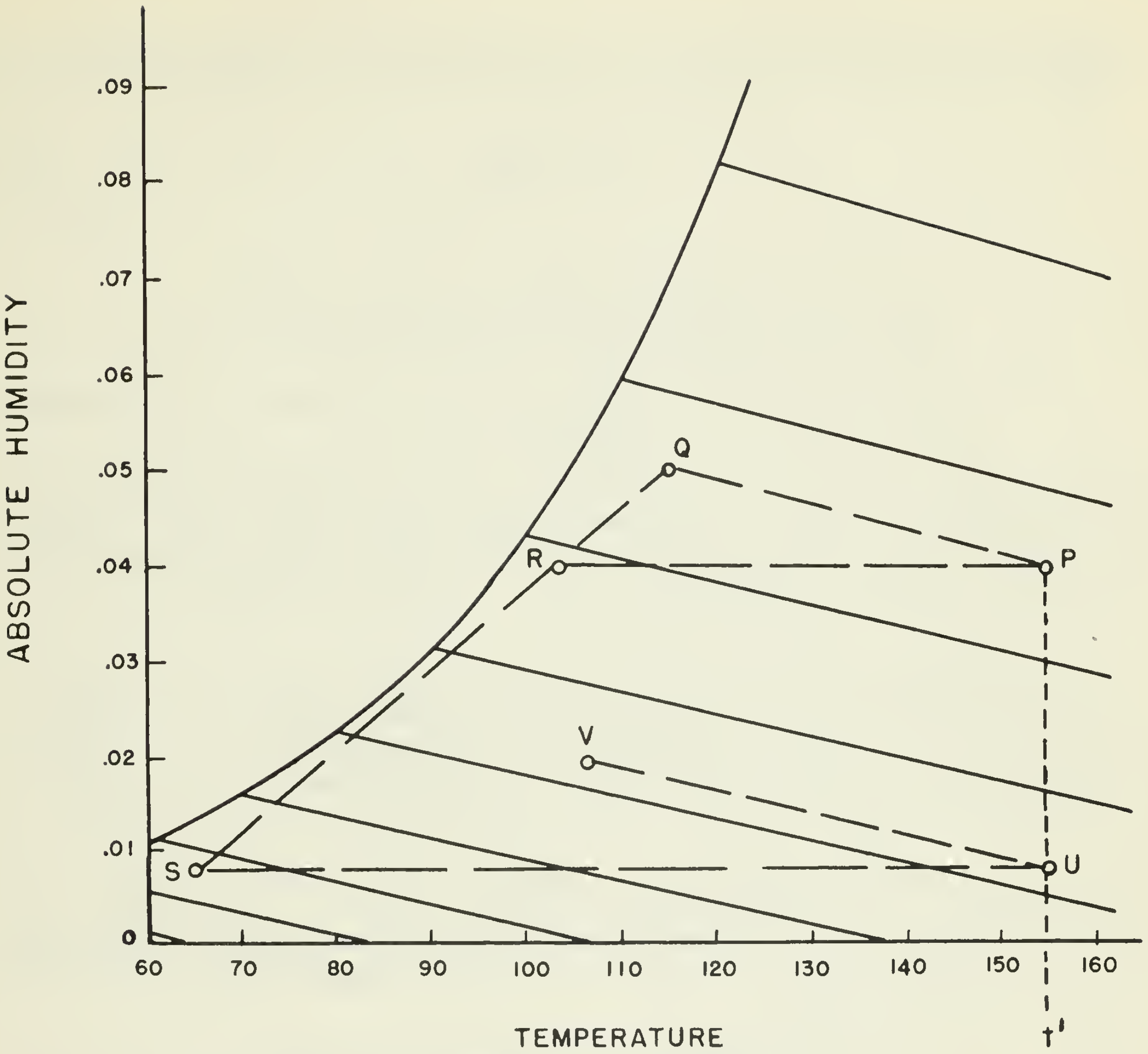

FIGURE 25-EFFECT OF RECIRCULATION ON TUNNEL CONDITIONS

conditions are reached, represented by points P, Q, and R on the chart. The air at the hot end of the tunnel will still be heated to the same temperature as before (t') but its humidity will be higher (P). In passing through the tunnel, its condition will change, at constant wet-bulb temperature, to that indicated by Q. The mixture of one-quarter fresh air and three-quarters exhaust air will be represented by R. The amount of heat required is represented roughly by the length of the line RP, which is much shorter than the one representing no recirculation, SU. The increase in wet-bulb temperature and the corresponding decrease in evaporative capacity and increase in drying time may be, however, only moderate.

The proportion of recirculation may be readily calculated if the absolute humidities are known, by the use of the following formula:[10]

$$r = \frac{a' - a_o}{a'' - a_o} \quad - - - - - - - - - - \quad (11)$$

r is the proportion of the circulating air that is recirculated,
$1 - r$ is the proportion of fresh air in the mixture,
a_o is the absolute humidity of the incoming, or fresh air,
a' is the absolute humidity of the mixture entering the hot end of the dehydrator, and
a'' is the absolute humidity of the air as it leaves the dehydrator, to be partly recirculated.

For example, suppose that a counterflow tunnel is operating at a wet-bulb temperature of 100°, a hot-end temperature of 165°, and a cool-end temperature of 137.5°. The fresh air drawn in has a temperature of 60° and a wet-bulb temperature of 55°. What are the proportions of recirculation and fresh air intake?

From the humidity chart, $a_o = 0.0080$, $a' = 0.0271$, and $a'' = 0.0337$. Then from equation 11, $r = 0.743$, or 74.3 percent, and $1 - r = 0.257$, or 25.7 percent. If air is circulating in the dehydrator at a flow of 2000 pounds per minute, the weight of fresh air drawn in will be 514 pounds per minute.

In a multiple-stage dehydrator the formula may be used by applying it separately to sections where conditions are known at both ends. For example, the "fresh air" supplied to the primary stage of a two-stage tunnel may consist partly or wholly of air exhausted from the secondary stage of the dehydrator.

Control of recirculation enables the operator to maintain substantially uniform drying conditions regardless of variations in atmospheric conditions. If the absolute humidity of the fresh air rises, the proportion of recirculation can be reduced to compensate for the change. Automatic control of wet-bulb temperature can be accomplished by making the controller operate recirculation dampers. However, the absolute humidity of outdoor air changes much less from hour to hour than the relative humidity, and wet-bulb temperature in the dehydrator can be held steady with relatively little attention to the recirculation so long as the rate of evaporation in the tunnel does not change materially. During starting-up and shutting-down periods, when the evaporation is abnormal, the proportion of recirculation must be changed drastically if anything like a uniform wet-bulb temperature is to be maintained.

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[10] The effects of air leakage from the dehydrator and water vapor added to the air by direct combustion of oil or gas fuel are neglected in this formula.

The reader must not conclude, from what has just been said, that recirculation of air in the dehydrator is to be recommended without reservations; the answer to the question "What proportion, if any, of the air flow in this dehydrator should be recirculated?" can be given only after several factors have been balanced against one another. The matter is discussed more fully in the following section.

IV-F. Heat Usage in Tunnel Dehydrators

The necessity of supplying from some source at least 1000 B.t.u. of heat for each pound of water evaporated has already been pointed out. It is not necessary that this heat be supplied from an artificial source; water evaporates from the washing hung on a clothesline without any consumption of fuel. But even in that case the heat required is taken from somewhere--from the air blowing past the clothes, which becomes cooler.

From the practical standpoint that type of natural evaporation is too slow and uncertain to be used for dehydrating vegetables, although it is extensively used in California for drying some fruits. Dehydration of vegetables is speeded up and made controllable through the application of artificial heat. In commercial dehydrators the heat supplied to the circulating air ranges between about 1500 and 6000 B.t.u. per pound of water evaporated. The requirement varies with the type of dehydrator and with the conditions of operation; it is partially within the control of the dehydrator operator.

The heat consumption of tunnel dehydrators may be estimated approximately from the following formula:

$$F = 1{,}250 \left[r + (1 - r) \frac{t' - t_0}{t' - t''} \right] \underline{11/} \quad - \quad - \quad - \quad - \quad (12)$$

In this formula,

F is the heat that must be supplied, B.t.u. per pound of water evaporated,
r is the proportion of air recirculated,
t_0 is the temperature of the incoming, or fresh air,

11/ The formula is based upon the fact that the incoming fresh air must be heated up to the hot-end temperature, while the recirculated air only requires reheating from the cool-end temperature to the hot-end temperature. The numerical coefficient 1,250 is the product of 5° (change in temperature per 0.001 increase in absolute humidity), divided by 0.001 (to convert to pounds of water evaporated per pound of air), and multiplied by 0.25 (approximate humid heat of the circulating air). It makes a reasonable allowance for ordinary heat losses.

t' is the temperature of the heated mixture of fresh and recirculated air as it enters the drying section of the dehydrator (hot-end temperature), and

t'' is the temperature of the air as it leaves the drying section of the dehydrator, to be partially recirculated (cool-end temperature).

For example, in the counterflow tunnel referred to in the previous section, $r = 0.743$, $t_o = 60°$, $t' = 165°$, and $t'' = 137.5°$. If those values are substituted in equation 12, $F = 2,150$ B.t.u. per pound of water evaporated. If this tunnel evaporates 20 pounds of water per minute the necessary heat input is 2,580,000 B.t.u. per hour.

The formula can, of course, be used to estimate the heat requirement of a multiple-stage tunnel provided the necessary information is available for each of the stages. Completely different and more complicated methods are necessary for estimation of the heat consumption of conveyor-type through-flow dehydrators and cabinet dehydrators; it is not feasible to describe them in this bulletin.

Even though this estimate makes some allowance for ordinary heat losses, the designed heating capacity of a tunnel dehydrator will normally be increased generously over the estimate in order to allow for air leakage and unforeseen exigencies of operation. Excess heating capacity will allow the operator a desirable degree of flexibility in choosing conditions under which the dehydrator shall work, particularly the wet-bulb temperature level. If the dehydrator is heated by an oil burner the design engineer should, of course, avoid installing such excessively large burners that they cannot be throttled down to probable low levels of heat demand without smoking.

Consideration of equation 12 brings out the following relationships:

1. The higher the proportion of recirculation, other things being equal, the lower will be the heat consumption per unit of evaporation.

In the above example, 74.3 percent recirculation in a counterflow tunnel when $t_o = 60°$, $t' = 165°$, and $t'' = 137.5°$ resulted in a heat usage of 2,150 B.t.u. per pound of evaporation. If all those temperatures remained the same, but no air was recirculated, equation 12 indicates that the heat usage would rise to 4,750 B.t.u. per pound of evaporation. The wet-bulb temperature in the tunnel would be reduced from 100° to 86°.

The practical case will be more complicated, because when the wet-bulb temperature is reduced the rate of drying will rise and the resulting cool-end temperature will be lower than 137.5°. The following more realistic example has been worked out from the nomographs for the drying of potato half-dice, published in bulletin AIC-31-VII:

Potato half-dice are to be dried in a counterflow tunnel from $T_0 = 4.20$ to $T_f = 0.06$. There are 3780 square feet of metal-bottom tray surface in the tunnel, and the product is spread at a loading of $L_0 = 3.0$ pounds per square foot. Air velocity at the cool end, where there are 33 square feet of free cross-section, is 1100 feet per minute. The hot-end temperature is to be 160°. Fresh air at the intake has a temperature of 80° and an absolute humidity of 0.0150. The tunnel is to be run in one case with no recirculation (reference to the humidity chart shows that the wet-bulb temperature in the tunnel will then be 90°), and in the other case sufficient recirculation is to be used to raise the wet-bulb temperature level to 110°. Determine the proportion of recirculation required in this second case, and compare the output of dry product, the heat consumption per pound of water evaporated, and the total heat input per hour for the two cases.

Calculation by methods already described gives the mass air flow through the tunnel as 2420 pounds of dry air per minute in both cases. Use of the nomographs and further calculation from the resulting estimates of drying times and cool-end temperatures for the two cases gives us the following comparisons:

Wet-bulb temperature, °F.	90	110
Recirculation, percent	0	84
Cool-end temperature, °F.	128.4	136
Drying time, hours	9.86	12.90
Dry product, pounds per hour	235	180
Heat required per pound of evaporation, B.t.u.	3,140	1,715
Heat input per hour, B.t.u.	2,900,000	1,200,000

For the conditions of this example, then, the heat demand of the dehydrator has been reduced by almost 60 percent, at a sacrifice in rate of product output of only about 25 percent. Reduction of the heat usage by more than half represents, of course, a substantial saving in operating cost. The operator must not forget, however, that when he raises the wet-bulb temperature in the dehydrator, as he does when he increases the recirculation, he may not only be increasing other operating costs, but he may also be injuring the quality of the dry product. The cost of the fuel used for the dehydrator is, after all, only a minor item in the total operating cost of the plant.[12] Some of the larger items of cost are fixed sums expended per day or per year, and the greater the output of acceptable product the lower will be the cost for these items which must be assessed against each pound of product. Sacrifice of 25 percent of the plant capacity would probably far outweigh the saving in cost of heat.

While a full discussion of the quality of the product as affected by wet-bulb temperature level and total drying time is outside the scope of this bulletin, it is a matter which must be taken most seriously.

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[12] W. D. Ramage and C. L. Rasmussen. This is what it costs to dehydrate vegetables. Food Ind. 15(7):64-71; 15(8):66-67; 15(9):75-77, July-September, 1943.

In general, we would expect the product which took 12.9 hours to dry at a wet-bulb temperature level of 110° to be inferior to the one dried in less than 10 hours at a wet-bulb level of 90°. The operator can make his own quality comparisons by carrying out experimental drying tests in a cabinet drier as described in section IV-C above.

In the author's opinion, the point of best balance for dehydrators run under conditions of low outside absolute humidity will usually turn out to involve some recirculation of the air. In the above example the assumed outside humidity was relatively high; no recirculation whatever might be the best all-around solution for that case.

2. For given conditions inside the dehydrator, the heat consumption per pound of evaporation will be higher if the fresh air supply is colder, or if its absolute humidity is higher.

Example: Consider conditions in the potato dehydrator of the preceding paragraph, maintained at 110° wet-bulb temperature, hot-end temperature 160°, cool-end temperature 136°.

a. The heat consumption when the fresh air has a temperature of 80° and absolute humidity of 0.0150 has already been calculated at 1,715 B.t.u. per pound of evaporation, 1,200,000 B.t.u. per hour. What will it be if the fresh air supply has the same absolute humidity, but is just saturated (100 percent relative humidity)--temperature 68°? The proportion of recirculation will remain the same as before, 84 percent, but the heat requirement will rise to 1,815 B.t.u. per pound of evaporation, 1,270,000 B.t.u. per hour, because of the lower fresh air temperature.

b. Maintaining the same conditions inside the dehydrator, what will the heat consumption be if the absolute humidity of the fresh air is 0.0060, temperature 80° (27 percent relative humidity, desert conditions)? The proportion of recirculation will now rise to 87.1 percent, heat required will fall to 1,625 B.t.u. per pound of evaporation, 1,140,000 B.t.u. per hour.

c. Maintaining the same conditions inside the dehydrator, what will the heat consumption be if the fresh air supply has a temperature of 90°, absolute humidity 0.0250 (82 percent relative humidity, tropical conditions)? The proportion of recirculation will fall to 78 percent, and the heat required will rise to 1,780 B.t.u. per pound of evaporation, 1,245,000 B.t.u. per hour. In this case the high absolute humidity of the fresh air more than offsets its somewhat higher temperature.

ACKNOWLEDGMENTS

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DEFINITIONS OF TECHNICAL TERMS

Absolute humidity. The quantity of water vapor in moist air, expressed as pounds (or grains) of water vapor per pound of dry air. (Page 8)

Absorption. One of the processes by which water vapor can be removed from moist air--specifically, the taking up of water vapor by a very strong solution of such a salt as lithium chloride. (Page 41)

Adiabatic. Adjective describing a process which goes on without either loss of heat to, or gain of heat from, the surroundings. (Page 67)

Adsorption. One of the processes by which water vapor can be removed from moist air--specifically, the taking up of water by the attraction of the solid surfaces of such substances as silica gel or activated alumina. (Page 41)

Anemometer. Any of several different kinds of instrument used for measuring air velocity. (Page 23)

B.t.u. (British thormal unit). The engineering unit of heat quantity. (Page 20)

Barometric pressure. The pressure exerted by the weight of the atmosphere above the observing station. (Page 18)

Cabinet drier. A type of drier in which a single tray or group of trays of wet material may be dried as a batch. (Page 72)

Case-hardening. A term borrowed from the lumber-drying industry, and which in that case signifies a condition of internal strains and sometimes surface checks, caused by too-rapid drying. In vegetable dehydration, the condition in which the surfaces of pieces are much drier than their interiors--not necessarily an undesirable condition. (Page 42)

Concurrent. The type of tunnel dehydrator in which both hot air and wet product enter the same end of the drier and move in the same direction. Means the same as "parallel-flow", and is the reverse of "counterflow". (Page 68)

Counterflow. The type of tunnel dehydrator in which the hot air enters one end of the tunnel, and the wet product enters the opposite end. The reverse of "concurrent" or parallel-flow". (Page 68)

Dehumidification. The process of removing water vapor from moist air. (Page 41)

Dew-point temperature. The temperature at which moist air, cooled without change in total pressure or change in composition, becomes saturated with water vapor. (Page 8).

Diffusion. The gradual movement of one substance within another; specifically, in dehydration, the gradual movement of water from the interior of a wet piece of material to the surfaces. (Page 30)

Diffusivity. A physical quantity which expresses the ease with which one substance will diffuse within another. (Page 31)

Drying ratio. The ratio of the weight of wet prepared material entering a drier to the weight of the same, nearly dry, material leaving the drier. (Page 26)

Equilibrium moisture content. The amount or proportion of moisture in a material which will neither increase nor decrease after indefinitely long contact with air of some specified temperature and humidity. (Page 38)

Humid heat. The quantity of heat (in B.t.u.) required to raise the temperature of one pound of dry air, plus whatever water vapor it contains, 1 degree Fahrenheit. (Page 22)

Humid volume. The volume, in cubic feet, of one pound of dry air plus whatever water vapor it contains. (Page 21)

Hygrometer. A type of instrument which indicates the humidity of air by means of the stretching or contracting of a length of hair or other organic substance. (Page 10)

Inversely proportional. The mathematical relation between two quantities such that if one of them increases the other decreases proportionally, so that their product will remain unchanged.

Latent heat of evaporation. The quantity of heat (in B.t.u.) absorbed when one pound of a liquid (in dehydration, water) evaporates. (Page 20)

Manometer. An instrument for measuring pressure, or more usually, pressure difference. In dehydrator work the manometer used to measure the difference in pressure between air in the dehydrator and the outside air may consist of a U-shaped piece of glass tubing containing a little water; if one side of the U is connected by tubing to the dehydrator space and the other side is left open to the air, the difference in water level in the two sides of the U indicates the pressure difference. A draft gage is one form of manometer. (Page 21)

Nomograph. A kind of diagram used for calculations or for expressing complicated experimental results in a form convenient for use. When points on two of the lines on the diagram are lined up with a straightedge, an answer is read from the point where the straightedge crosses a third line. Synonomous with "alinement chart". (Page 47)

Parallel-flow. The type of tunnel dehydrator in which both hot air and wet product enter the same end of the drier and move in the same direction. Means the same as "concurrent", and is the reverse of "counterflow". (Page 68)

Partial pressure. That part of the total pressure of a gas or vapor which is contributed by one of its constituents. (Page 5)

Proportional. The mathematical relation between two quantities such that if one of them rises or falls the other one also rises or falls proportionally, so that their quotient will remain unchanged.

Psychrometer. Any type of instrument which measures or indicates the humidity of air. (Page 13)

Recirculation. The re-use of part of the warm, moist air leaving the drying zone of a dehydrator; mixed with some fresh air and reheated, it is returned to the drying zone. (Page 78)

Relative humidity. The ratio (usually expressed as percentage) of the partial pressure of water vapor in moist air to the vapor pressure of water at the same temperature. (Page 6)

Retention time. The length of time each truck, or each piece of product, remains within a dehydrator. (Page 70)

Saturated. The condition of a vapor space or a body of air in which, even in the presence of a liquid such as water, no additional net increase in the amount of vapor in the space will occur by further evaporation of the liquid. (Page 4)

Specific heat. The quantity of heat (in B.t.u.) required to raise the temperature of 1 pound of a substance 1 degree Fahrenheit (practical definition, not exact). (Page 22)

Specific volume. The volume (in cubic feet) of 1 pound of a substance. (Page 21)

Thermocouple. A temperature-indicating device, comprising two wires of dissimilar metals twisted together to form the sensitive element. An electrical instrument such as a potentiometer is used to detect the slight voltage difference which appears when the junction is heated. (Page 24)

Total pressure. In a gas or vapor, the pressure exerted on all walls of the container by all of the constituents acting together. (Page 5)

Vapor pressure. The pressure exerted by pure vapor in equilibrium with the substance named. For example, the vapor pressure of water at 212° F. is 29.92 inches of mercury, or one atmosphere, and is the pressure of water vapor in equilibrium with liquid water at 212° F. (Page 4)

Vapor pressure isotherm. In dehydration, the curve representing the relationship of the water vapor pressure of a partly dry material to the moisture content of the material, at a constant temperature. (Page 38)

Wet-bulb depression. The difference in temperatures between dry-bulb and wet-bulb thermometers exposed to the same air stream. (Page 12)

Wet-bulb temperature. The temperature indicated by a thermometer exposed to an air stream under standard conditions if the sensitive bulb of the thermometer is kept constantly moist with pure water. (Page 12)